# Electrical Engineering

June
1939

Published Monthly by the
American Institute of Electrical Engineers

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*G-E pressure-gage equipment, set up for calibration with a G-E Type PM-10 oscillograph*

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HEADQUARTERS FOR ELECTRICAL MEASUREMENT

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430-143

# Electrical Engineering

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## *for June 1939—*

**The Cover:** One of the two Elephant Towers at the main entrance, and the 400-foot Tower of the Sun, at the Golden Gate International Exposition, a feature attraction of the AIEE combined summer and Pacific Coast convention to be held June 26–30, in San Francisco, Calif.

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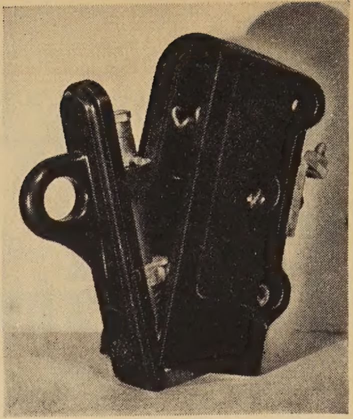

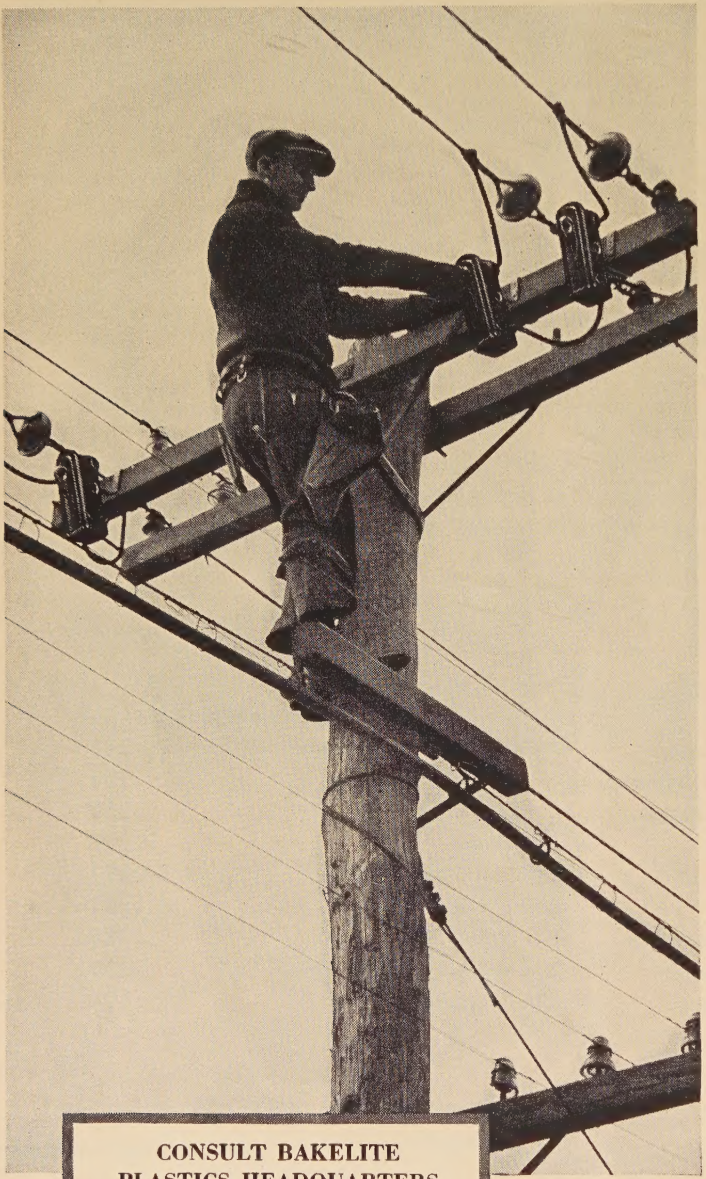

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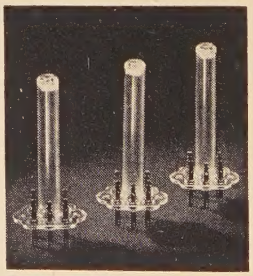

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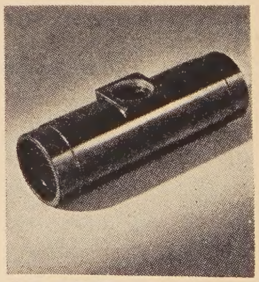

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# High Lights

**Synthesis of Color.** Exposition lighting on Treasure Island in San Francisco Bay will be one of the feature attractions of the Institute's forthcoming summer convention. Through the generous co-operation and collaboration of the General Electric Company and *Architectural Record*, ELECTRICAL ENGINEERING is able to present in this issue a group of four-color reproductions of effects created at the Golden Gate International Exposition through the masterly use of electrical illumination. Technical data and explanations have been drawn from the text of a technical program paper scheduled for presentation at the convention (*pages 234–50*).

**Lightning Performance.** An AIEE subcommittee has gathered data on the lightning performance of transmission lines operating in the United States and Canada at voltages from 110 kv to 165 kv, from which the benefits of various means of protection may be evaluated (*Transactions pages 294–306*).

**Fiber Glass Insulation.** Textiles woven from fibers of glass have some advantages over those from organic fibers and asbestos for use as electrical insulation. Operation at higher temperatures than can be withstood by organic fabrics is possible, up to limits imposed by the impregnant used (*Transactions pages 277–86*).

**Asbestos and Glass Insulation.** Magnet wire insulated with asbestos fibers has become well established by long use; recently wire insulated with glass fibers has been introduced for use where temperatures are high. Temperature limitations, however, must be studied in terms of many related factors (*Transactions pages 290–4*).

**Mica Insulation.** A mineral widely used for high-temperature insulation is mica, which may be split into films as thin as 0.0003 inch; thin films are assembled into large sheets with the aid of suitable binders. The solid, nonporous structure offers some advantages over other flexible inorganic materials (*Transactions pages 287–9*).

**Thomson Commemorated.** At a recent meeting of the American Philosophical Society, the memory of Elihu Thomson was honored by presentation of several papers, each dealing with a different phase of his life. His achievements as an electrical engineer were related by a prominent AIEE member (*pages 251–5*).

**Bus Protection.** Several recent experiences with faults on power-station busses have shown the desirability of relay protection, to which little attention had been given because of the assumed relative freedom from faults and the possibility of incorrect tripping. Differential relaying may be used (*Transactions pages 243–52*).

**Battery Chargers.** Air conditioning of railroad cars has increased greatly the demands on the car storage battery, and has made necessary the charging of batteries on standing cars from power circuits. Dry rectifiers of the magnesium-copper sulphide type with forced cooling have been built for this purpose (*Transactions pages 260–5*).

**Standards.** In an effort to acquaint the membership more fully with the standards activities of the Institute, the AIEE standards committee is sponsoring a series of articles. This month's contribution discusses the place of the International Electrotechnical Commission in electrical standardization (*pages 272–3*).

**Modulators.** Improvements in copper-oxide rectifiers have led to their use as modulators in carrier telephone systems, where they replace vacuum tubes; no power is required, but numerous effects are found that ordinarily are not important in the tube arrangements (*Transactions pages 253–60*).

**Local AIEE Activities.** A total of 635 Section meetings was reported to AIEE headquarters during the fiscal year just ended, the largest number ever reported; the number of Branch meetings was somewhat less than were reported during the two preceding years (*pages 268–71*).

**Summer and Pacific Coast Convention.** Final plans for the AIEE combined summer and Pacific coast convention are rapidly nearing completion, and the complete tentative technical program has been announced (*pages 268–71*).

**Railway Relay Protection.** Electrification of the Pennsylvania Railroad from New York to Washington, D. C., and Harrisburg, Pa., necessitated the solution of new problems in relays (*Transactions pages 266–77*).

**District Meetings.** Brief reports of the meetings held by the Institute's South West and North Eastern Districts appear in this issue. Both meetings included District student conferences (*pages 263–4; 266–7*).

**Transformer Standards.** Several departures from previous standards are involved in new proposed standards for transformers, regulators, and reactors (*Transactions page 289*).

**Faraday Medal.** W. D. Coolidge (A'10, M'24) recently received the Faraday Medal for 1938; he is the third American to be so honored since the medal was established in 1921 (*pages 258–62*).

**Sound Measurements.** Sound-level measurements at some 900 different locations provide useful information concerning the noise in residences, large business offices, and factories (*pages 255–7*).

**Paper Prizes.** National prize awards for papers presented at Institute meetings during 1938 have been announced (*page 271*).

**Coming Soon.** Among special articles and technical papers undergoing preparation for early publication are: an article on the electric strength of fibrous glass, by Andrew Gemant and F. A. Glassow; an article discussing synthetic insulating materials and their application to wires, by Winton Patnode, E. J. Flynn, and J. A. Weh; an article describing a bridge for separating the components of traveling waves, by H. E. Hartig (M'30) and Cledo Brunetti; an article on the calculation of terminal voltage of synchronous generators for various overexcited power factors, by S. H. Wright (M'34); a paper on electromagnetic-horn design by L. J. Chu (A'39) and W. L. Barrow (M'33); a paper describing an electronic control circuit for resistance welders by T. S. Gray (M'38) and J. Breyer, Jr. (A'38); a paper on cold-cathode gas-filled tubes as circuit elements by S. B. Ingram (M'38); a paper describing electric drives for supercalenders in paper mills by R. H. Smith (M'36); a paper describing a system of polyphase radiobroadcasting by J. F. Byrne (A'32); a paper on a reverse-rotation test for the determination of stray-load loss in induction machines by T. H. Morgan (M'31), W. E. Brown (A'39), and A. J. Schumer (A'39); a paper describing a 12-channel carrier telephone system for open-wire lines by B. W. Kendall (F'29) and H. A. Affel (M'23); a paper describing a simplified precision resistance-welder control by F. H. Roby (A'37); a paper on low-gas-pressure cable by G. B. Shanklin (M'29); and a paper on progress of a-c arc welding by C. J. Holslag (M'19).

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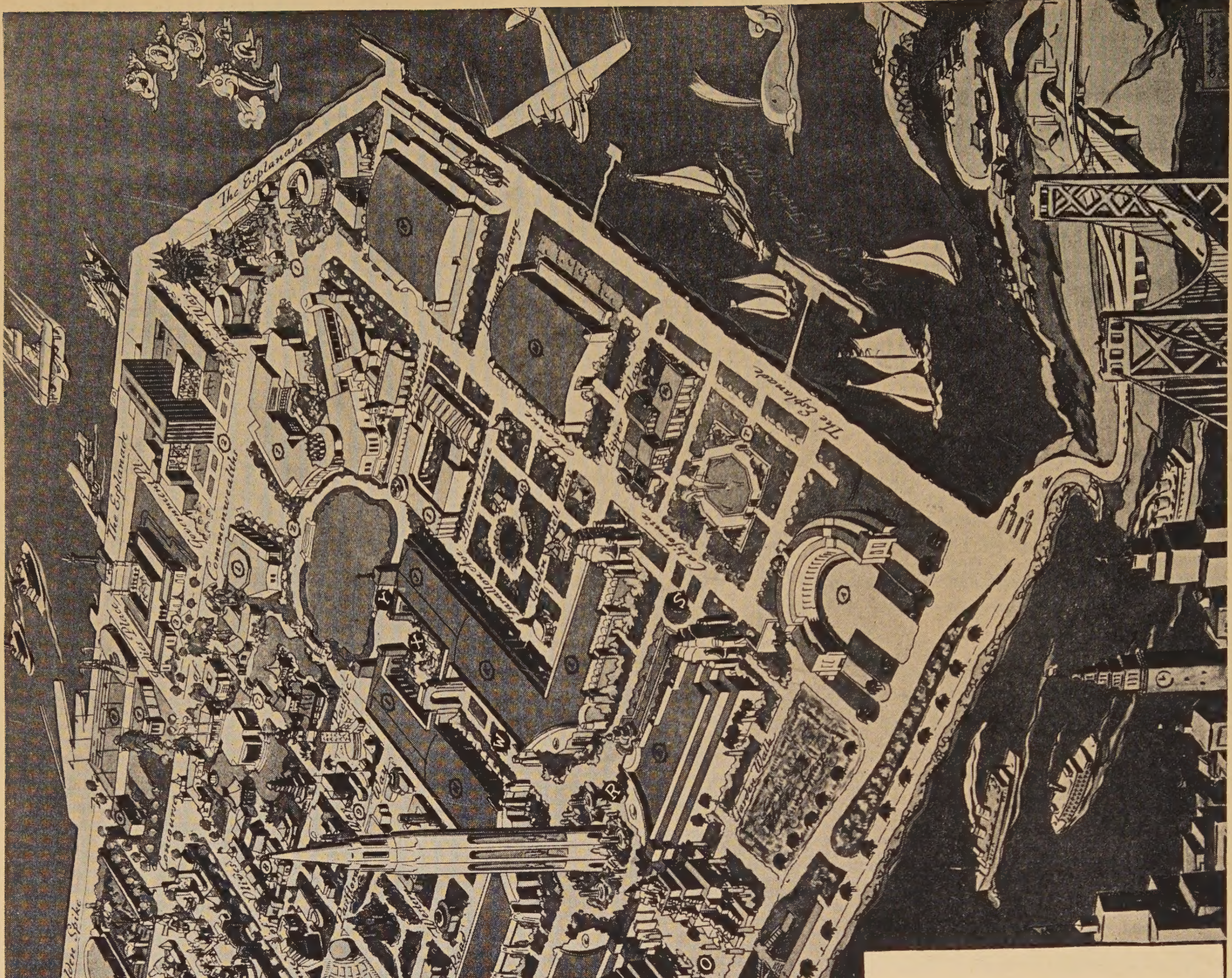


## Treasure Island, San Francisco

A modified cartograph of the Golden Gate International Exposition, marked to locate the settings of the color pictures that appear on the following pages

| Symbol | Designation | Color Plate |
|---|---|---|
| X | Court of Flowers | Plate 1 |
| V | Court of Pacifica | Plate 3 |
| O | Elephant Towers | Plate 5 |
| Y | Cambodian Towers | Plate 6 |
| W | Reflecting Pool | Plates 7 & 8 |
| S | Court of the Moon | Plates 9 & 10 |
| R | Tower of the Sun | Plate 11 |

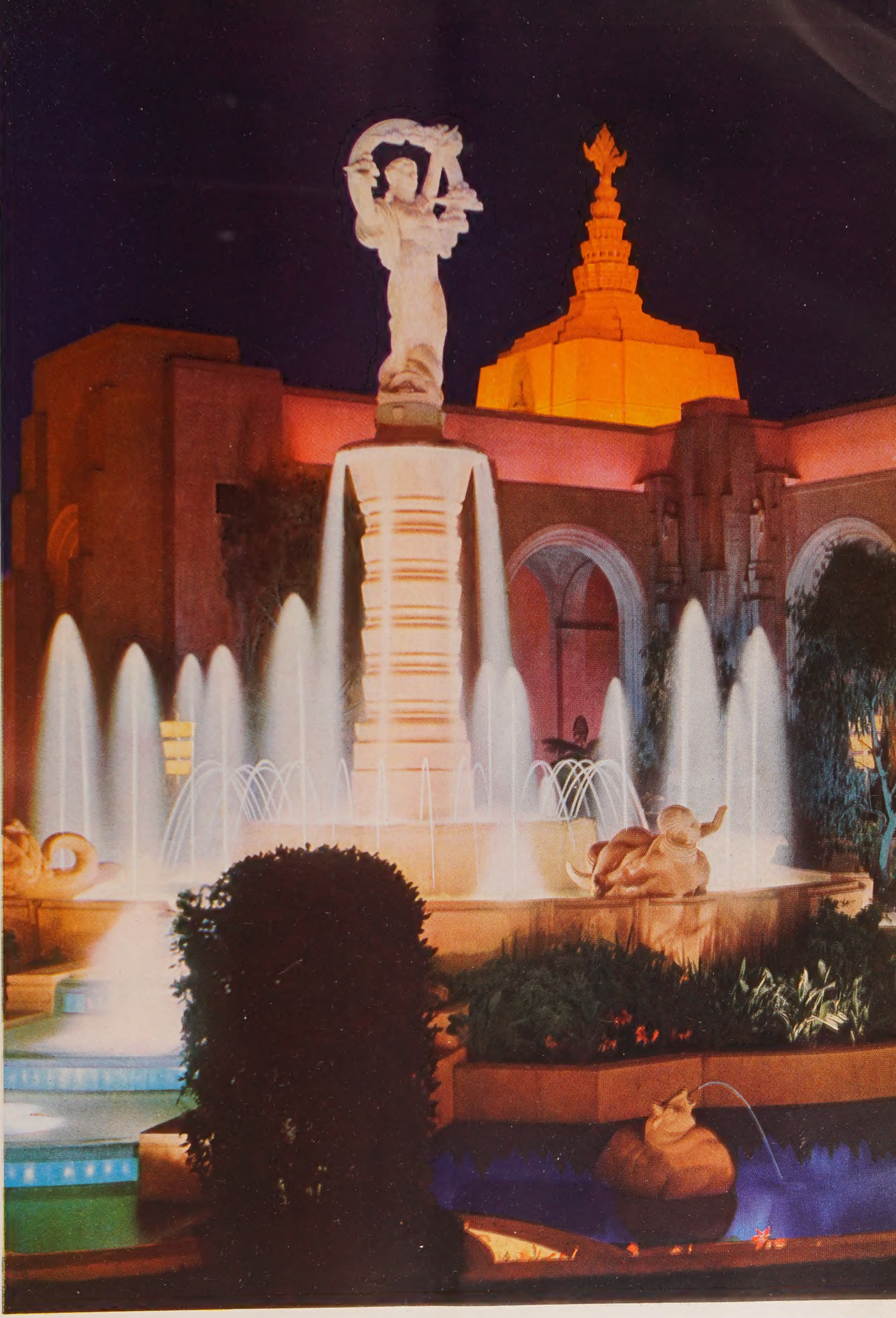


PLATE 1: "Court of Flowers:" Louis P. Hobart, Architect.

# COLOR: NEW SYNTHESIS IN THE WEST

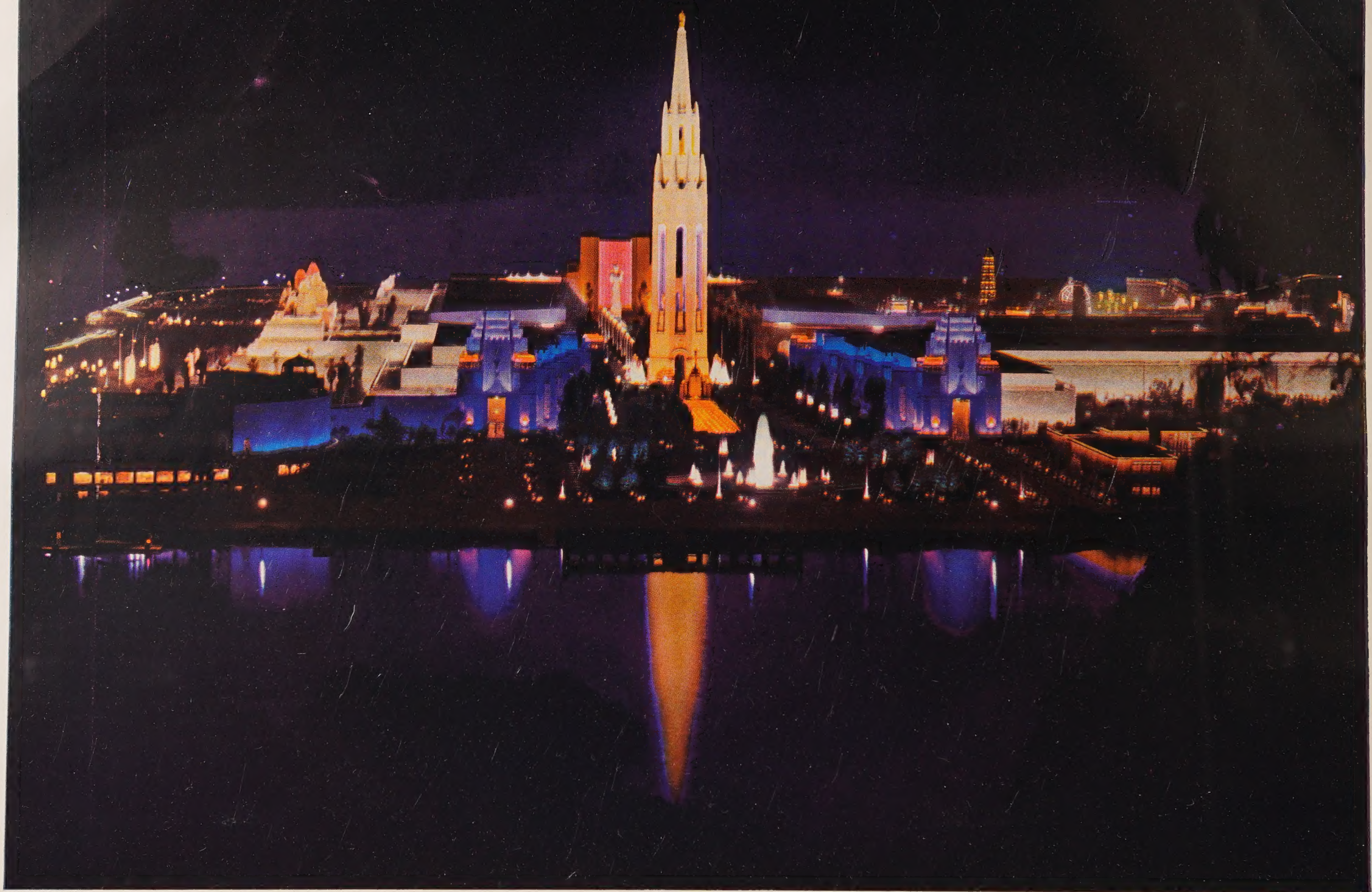


PLATE 2. One of the most dramatic aspects of the Golden Gate International Exposition (seen here from Yerba Buena Island) is the clear integration of the exterior illumination system with the architectural design. Note the careful organization of both colors and intensities, the visual sequences achieved thereby, the subdued and largely decorative role of street lighting.

# COLOR, LIGHT AND STRUCTURE AT GOLDEN GATE EXPOSITION

**by A. F. DICKERSON,**
***Director of Illumination****

Almost unnoticed, the rapid development of new illuminants and lighting equipments has, in the recent past, added a distinct and prodigious dimension to the field of exterior illumination—that of color. But precisely because the application of color to buildings is both a complex and unevenly explored field, available examples are few and often inconclusive. A notable exception is this year's Golden Gate International Exposition. Here—with a scale and completeness seldom approached before—is an artificial illumination system which is an integral part of the project design. Mr. Dickerson's paper thus not only describes an illumination project of interest to light specialists but constitutes reference material of prime value to building designers, engineers, and others. All photographs were specially taken by Gabriel Moulin for ARCHITECTURAL RECORD.

EACH OF THE great American expositions has marked progressive advances in the field of artificial illumination. Chicago's Columbian Exposition of 1893 startled the world with its wide use of the then-novel incandescent lamp. In 1915 the Panama-Pacific Exposition in San Francisco reached new levels in the use of exterior floodlighting. Chicago's Century of Progress showed further advances, particularly in the field of color. But it is safe to say that the current expositions employ a wider variety of new illuminants, equipments, and installations than all their predecessors combined. The Golden Gate International Exposition furnishes dramatic proof of such advances; and because the problems involved are applicable to all building design, description of its principal features seems worthwhile.

**Daylight color:** A standard palette of 19 colors and gold was adopted—with ivory, brown, gold and blues predominating. Seven colors are body or foundation colors; eight are used for embellishment of minor architectural features, four and gold for trim. Tints and shades, rather than pure colors, are employed throughout. All body colors are warm, with light intensities — yellow, ivory, fawn, ecru, taupe, brown, and blue; the secondary colors include yellow, jade (light and dark), emerald, four additional blues, red, mauve, and apricot.

In the majority of cases, this color was applied in pigment form in the plastered surfaces, in paint form on trim and detail. The plaster itself has an unusual luminosity, an effect achieved by pressing a mica product into plastered surfaces. The mica had first been heated to a high degree so that it became flaky and the laminations tended to separate. The result is a breaking up of the wall surfaces into innumerable small holes with a high reflective factor.

**Night color:** The artificial illumination must be understood as being superimposed on a base of the colors and surfaces described above. But the night color *does not seek to reproduce that of natural daylight.* On the contrary, many of the most successful effects are achieved solely with colored illumination on near-white surfaces. Compare, for example, the daylight and night colors of the Court of Pacifica (Pl. 3 and 4). Nor do the various *intensities, shadows, and silhouettes seek to duplicate those of natural daylight.* In fact, the illumination may be said to yield an additional—and entirely new—design over and above that of daylight.

The basic consideration in designing the illumination of the Exposition was to make it a truly integral part of the building design. Such integration of light and structure implied much more than mere concealment of the light sources, or avoidance of glare and shadows. That it has been achieved—and with spectacular success in installations such as that of the Court of the Moon (Pl. 9) and the Elephant Towers (Pl. 5)—is apparent. Here color achieves a luminosity which appears as coming from *within* the building rather than of being applied from *without.*

Once inside the bright exterior walls, the visitor moves through a series of color effects in a succession of walled courts—each lighted differently, with a harmony which makes the transition from one to another easy, yet distinct. In these courts, lighting has been used to fit the visitor psychologically to enjoy the setting. Emotions are excited toward gaiety by shades of red, rose, orange, and yellow—while greens, blue greens, and blues are used as tranquilizers. Colors are always in harmony and restricted in number from any viewpoint. Highlights, shadows, and silhouettes break up the monotony of the usual flatness of floodlighted surfaces. Advantage has been taken of every flag, niche, or unusual architectural element, to introduce a change of color or a highlight in order to increase the liveliness of the night scenes. Fountains throughout the grounds are illuminated, usually in static colors excepting in the Court of Pacifica (Pl. 3) where a shifting color cycle is controlled by thyratrons. In many places trees have been lighted by concealed mercury floodlights; but in general they count as dark masses against light.

**Installations and fixtures:** While the effect of the Exposition's illumination system may often appear extravagant, construction and operation were in fact relatively simple and inexpensive. All equipment is commercially available, including a weather-proof low-cost searchlight and a low-cost fluorescent floodlight, both of which were especially developed by General Electric for the Exposition. The various installations are in common use in ordinary commercial buildings: *floodlighting*—in trenches, set-backs, soffits, etc.; *spotlighting* of architectural features—towers, sculpture, niches, etc.; *groundlighting* by means of light standards and recessed fixtures; *water lighting* by underwater floodlights, lip lighting, etc. The chief interest here lies largely in demonstrating the extraordinary versatility possible with careful study at a sufficiently early stage.

But each of these installation types represents a high degree of specialization so that, when properly integrated, there is little need for supplementary lighting. This explains the relative unimportance of street-lighting units in the illumination design. In the major courts, these units serve more as architectural features than as sources of illumination. Outside the courts, street-lighting units of a more utilitarian character are used.

**Illuminants:** The range of lighting media includes all commercially available sources — incandescent, lumiline, arc, mercury- and sodium-vapor, neon, fluorescent, and ultra violet "black light" for use with luminescent paints. These media were used singly and in combinations, depending upon the colors, changes, and intensities desired. Quantitatively the most important were incandescent and fluorescent lamps — the specially developed fluorescent floodlights being widely used.

All illumination designs shown are by General Electric's Illuminating Laboratory.

---

*The overall design of day-and-night color is the end product of close co-operation between the following Exposition officials: W. P. Day, Director of Works; Jesse E. Stanton, Director of Color; Edward L. Frick, Chief of Division of Architecture; William R. Van Bokkelen, Chief of the Electrical Division; George E. Garthorne, Assistant Chief and in charge of Exterior Illuminations; the entire Architectural Commission under the chairmanship of Arthur Brown, Jr.; and Mr. Dickerson, Director of Illumination.

No novice in the field, Mr. Dickerson played an important part in the illumination of the Panama-Pacific Exposition of 1915, the Brazilian Centennial in 1922, A Century of Progress in 1933, and in floodlighting of Niagara Falls. Since 1932, he has been head, Illuminating Laboratory and Lighting Sales of the General Electric Company at Schenectady, N. Y.

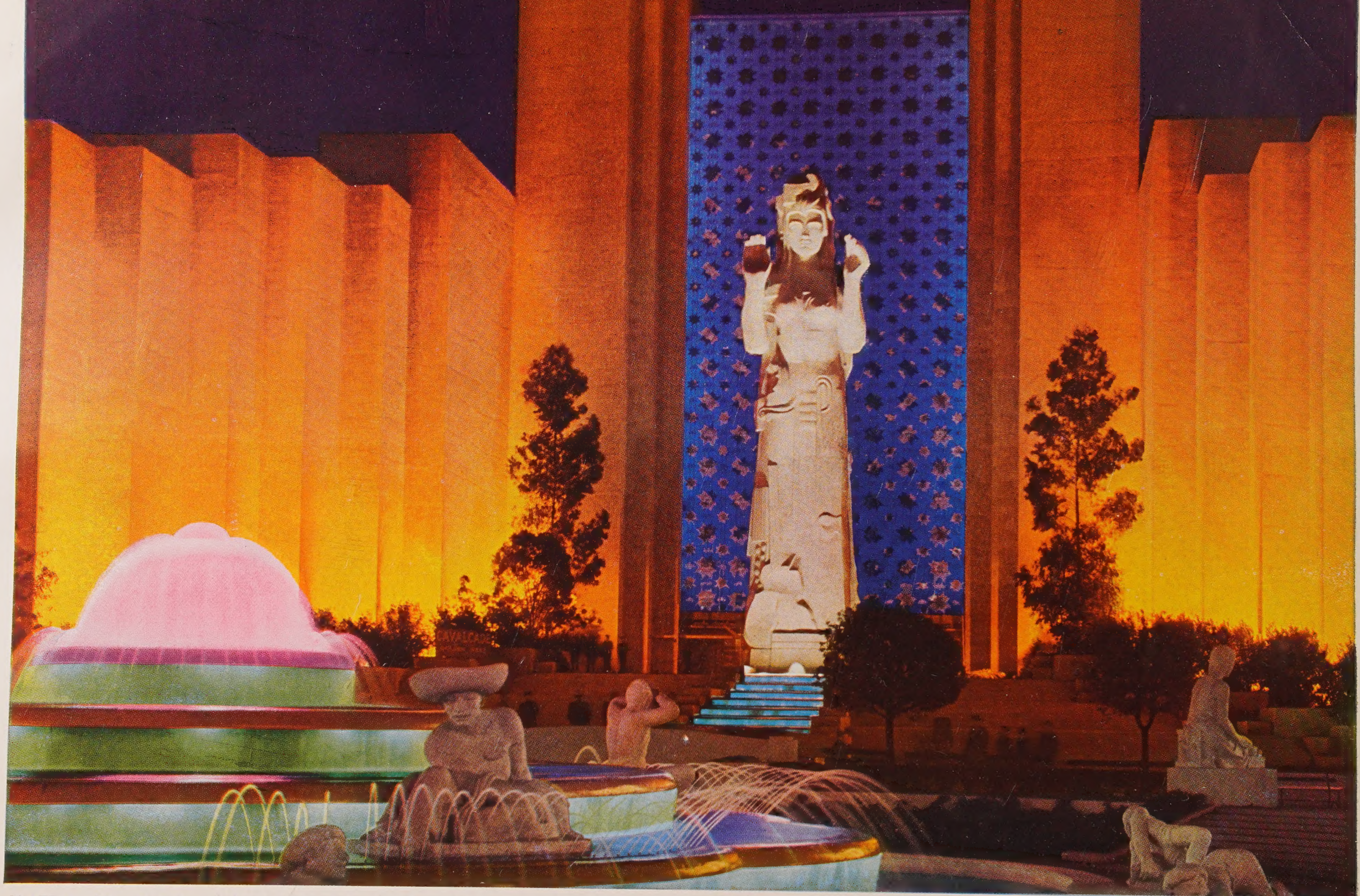


PLATE 3. Vivacity is here achieved not only by a wide variation of color and intensity of light but also by its movement. Synchronized thyratron controls give smoothly changing yet steady emphasis to the two most important architectural features—the statue and the fountain. Backgrounds have even values and harmonized colors which silhouette the planting.

# THE COURT OF PACIFICA

TIMOTHY L. PFLUEGER, Architect

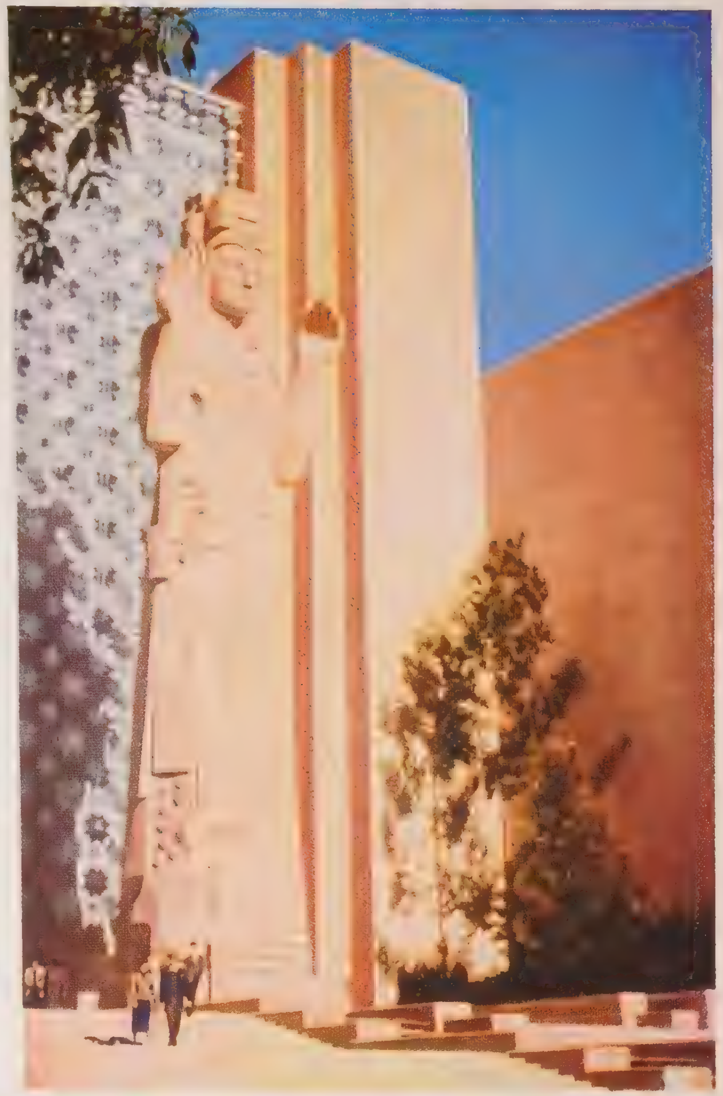


PLATE 4. This daylight view serves as a point of reference as regards the daylight-color base on which illumination is superimposed. All structures illustrated have similar colors and values.

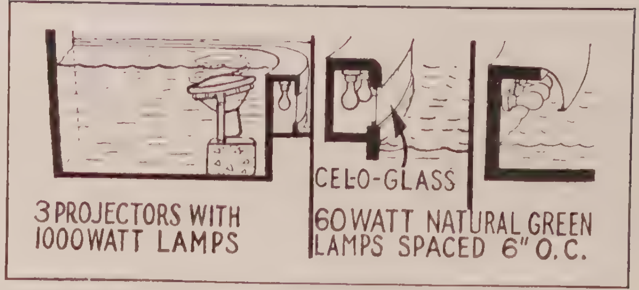


FIGURE 1

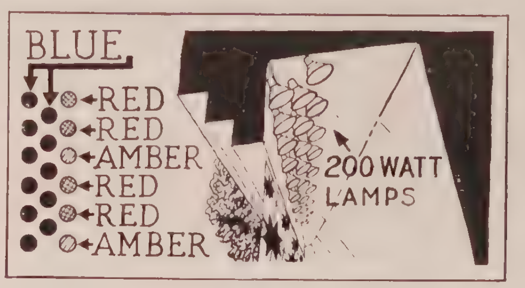


FIGURE 2

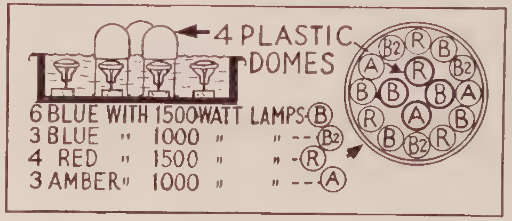


FIGURE 3

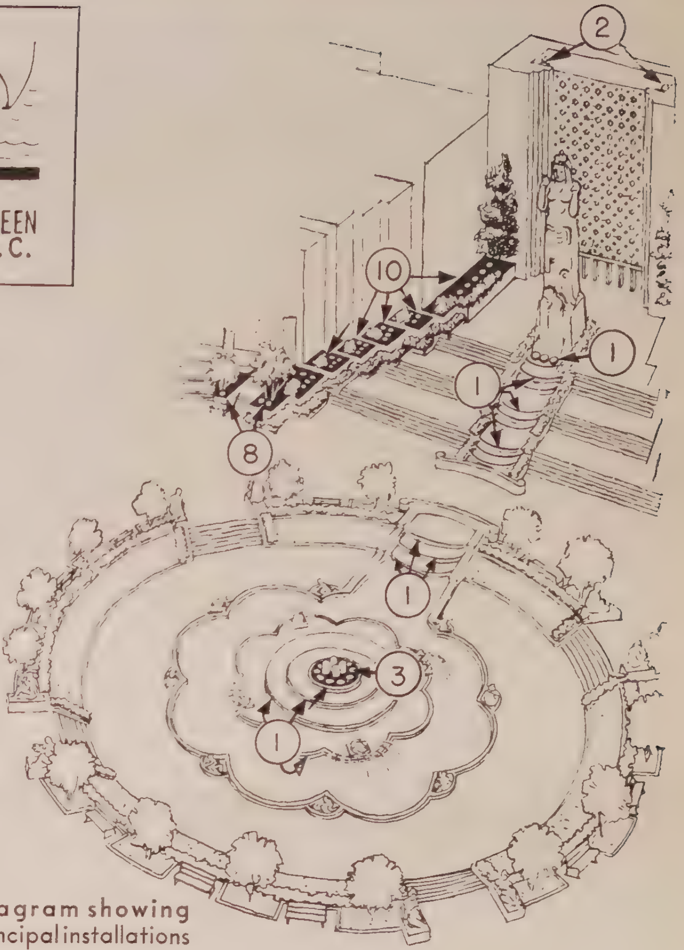


Diagram showing principal installations

The design of this court, as well as its location adjacent to the most popular entrance to the Exposition, called for a lighting treatment tending toward the spectacular. The chief installations of the illuminating system are:

The Great Window with its stainless-steel screen and plaster backdrop lit by 75 amber, 150 red, and 300 blue 200-w. floods controlled by thyratrons. (Fig. 2);

Robert Stackpole's 85-ft. statue. "Miss Pacifica." lighted by two 1500-w. underwater floods (Fig. 1);

The cascades and central fountain, with lip lighting of green and changing colors from underwater floods where there are jets. (Figs. 1 and 3);

The 80-ft. walls flanking the Grand Stairs and also the walls of the East Entrance are flooded in a golden amber (similar to Fig. 10);

Sixteen 86-ft. cylindrical lanterns (not shown) of Glyptal-treated fabric shed a warm glow that completely envelopes the Court. Each lantern has three-hundred 60-w. lamps, or a total of 288 kws. is used for the 16 standards (design similar to Figs. 6 and 7);

All of the main trees are lighted with 250-w. mercury floods concealed in ground cylinders (Fig. 8);

The East Entrance and the Gayway Plaza are lighted by decorative units with tiers of amber-orange lamps and banners. This exposed lighting furnishes a transition to the Amusement Section. Approximately 550 kws. of lighting are used in this Court.

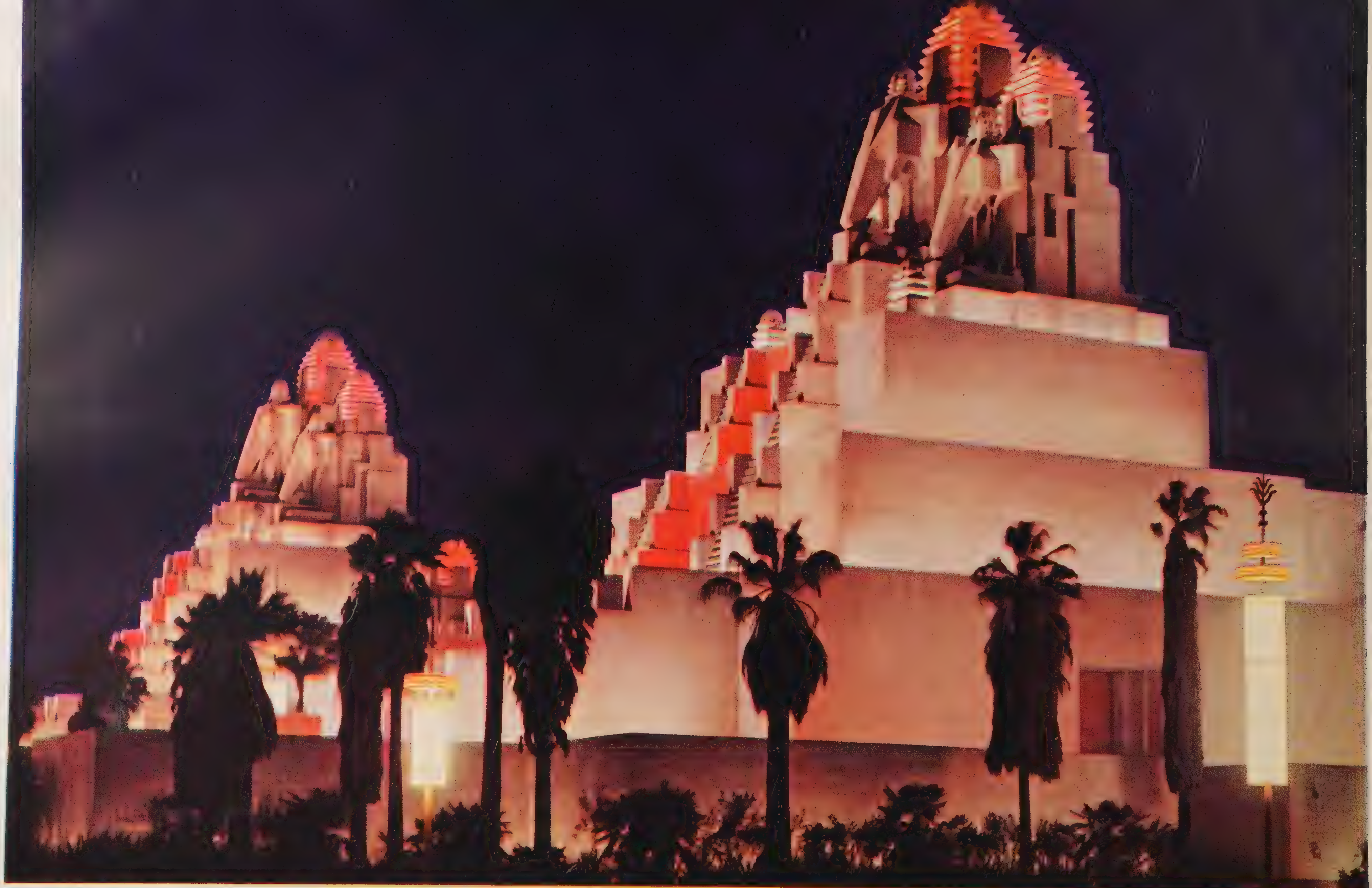


PLATE 5. Highest intensities and lightest colors have been widely used on those elements primarily designed to be seen from afar. Thus the brilliantly lit West Facade, with its monumental entrances, actually serves as a huge sign which dominates the city's eastern horizon and intersects its traffic lanes to the mainland. Colors are concentrated at the entrances.

# THE ELEPHANT TOWERS AND WEST FACADE

ERNEST E. WEIHE, Architect

The West Facade, for its entire distance of 3600 ft. from the Administration Building north, is floodlighted in white with color reliefs at the South Tower, main Elephant Tower entrance, ferry entrance, and in the seven large green circles above the entrances. Thirty cylindrical lanterns, 50 ft. in height with 4920-w., and 102 similar small lanterns, 18-ft. high with 1620-w., add a festive note to this area. These lanterns are all steel framework on steel poles with decorated Glyptal-treated fabric as the transparency (Figs. 6 and 7).

The main wall is lighted by Novalux L-49 floods with polished Alzak-processed reflectors, asymmetric lenses and 500-w. I. F. MAZDA lamps. These are spaced on 10-ft. centers, 15 ft. from the base of the wall, in a specially provided trench that is completely concealed by trees and shrubbery. (Similar trenches of various widths are used for all floodlighting throughout the Exposition. See Fig. 10.) In general, illumination values increase with height (Pl. 5): on the first set-back 200-w. floods with etched reflectors and clear lenses are used on 8-ft. centers; 300-w. floods on 10-ft. centers light the second set-back (Fig. 5). The elephants themselves are picked up with 18-in. incandescent searchlights equipped with 1500-w. floodlighting lamps (Fig. 21). The louvered "howdahs" are in red, with 60-w. natural ruby incandescent lamps 12-in. o.c. (Fig. 4).

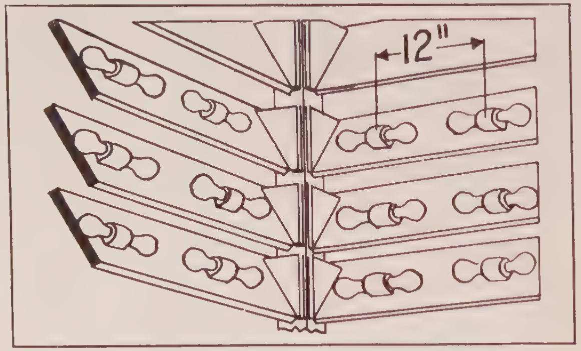


FIGURE 4

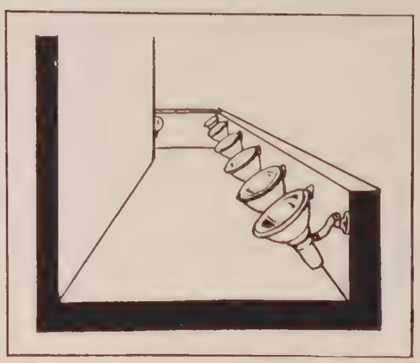


FIGURE 5

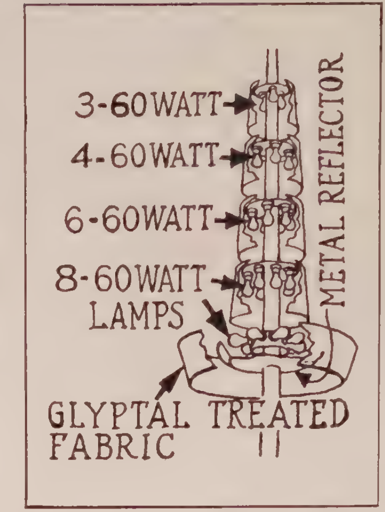


FIGURE 6

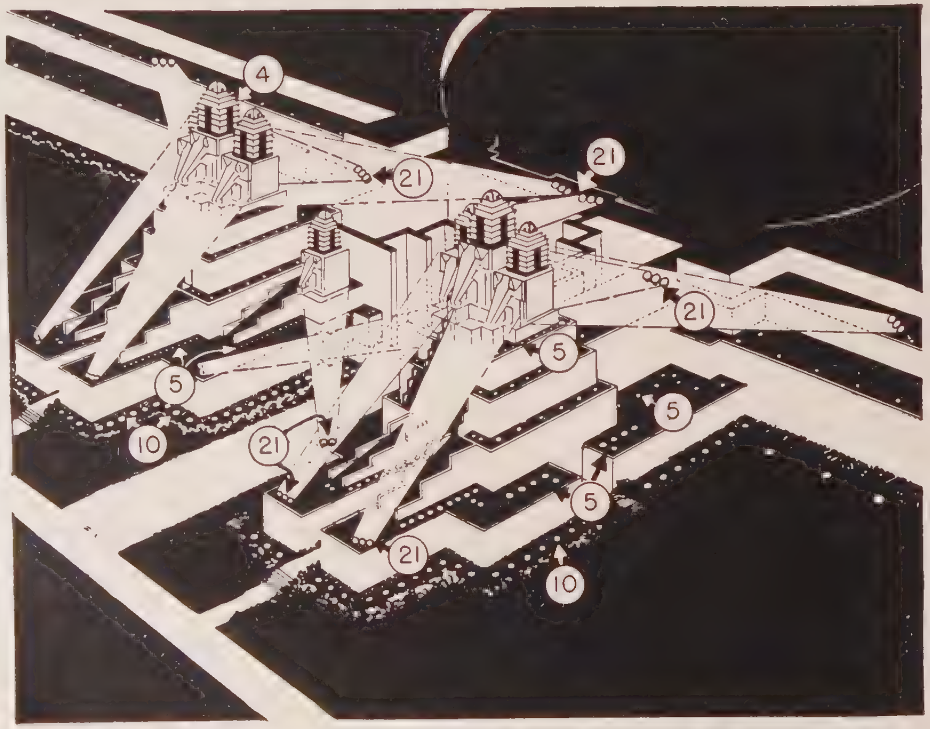


Diagram showing search- and floodlight locations for Towers and West Facade

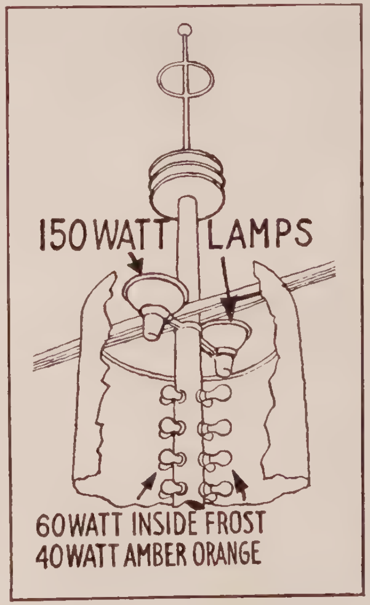
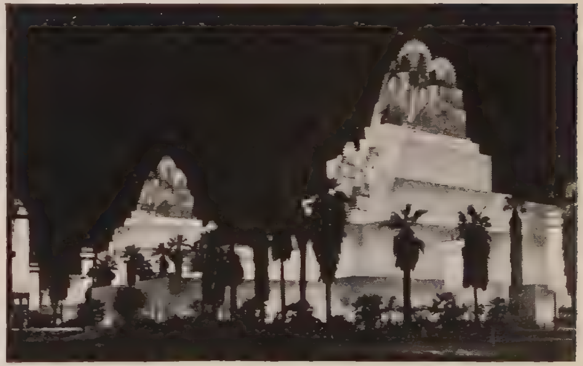


FIGURE 7



White light on the cream plaster yields surfaces whose values are approximately equal to those of daylight

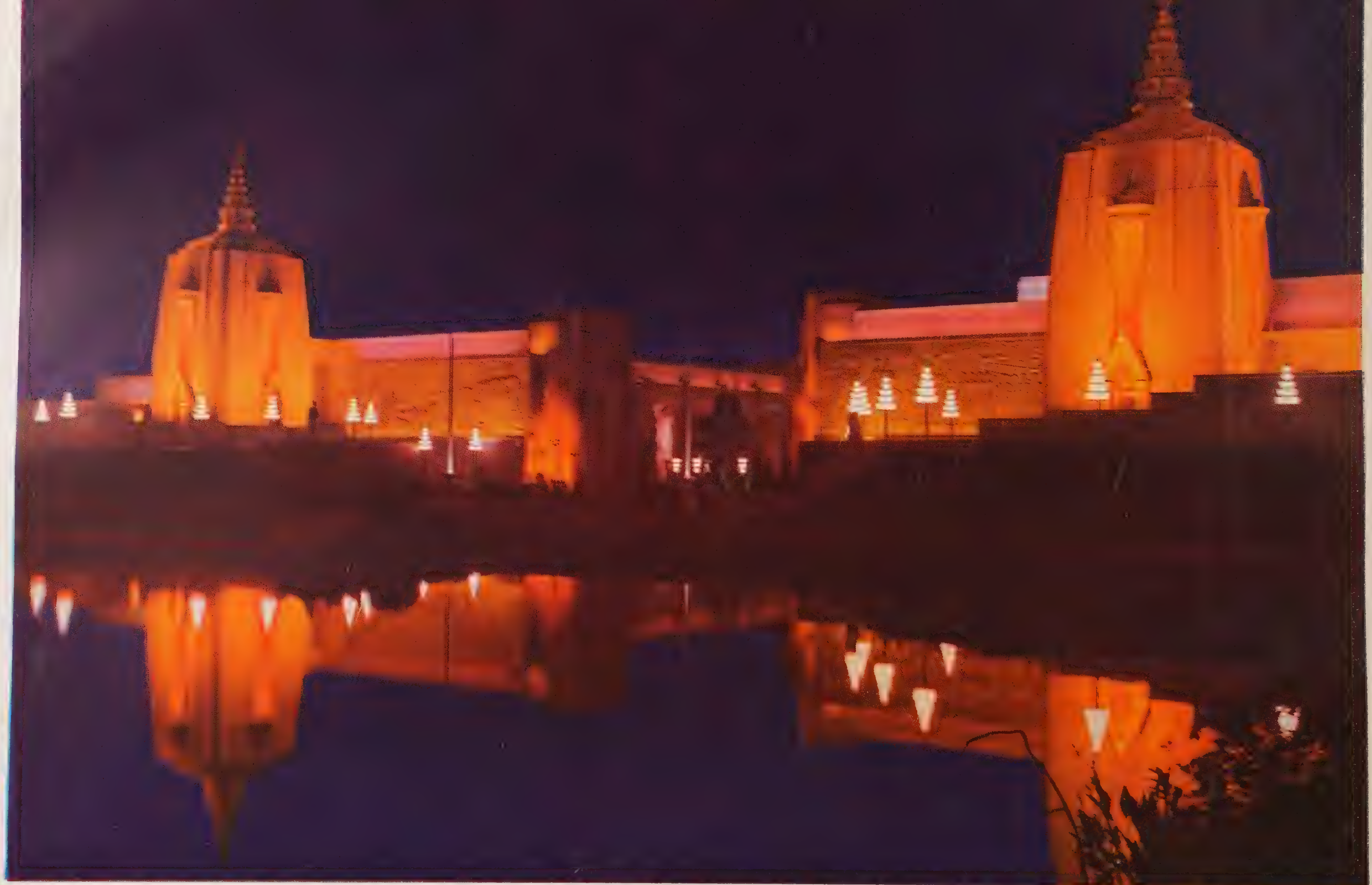


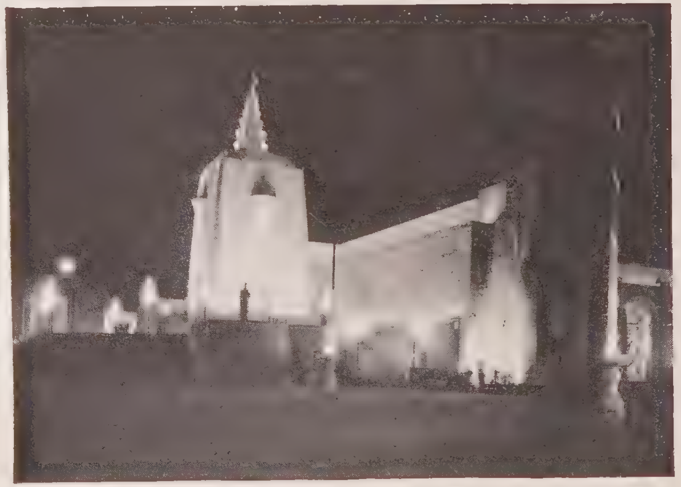
PLATE 6. The richly textured golds of Lulu Braghetta's and Jaques Schnier's bas-reliefs are carried in pink, the towers in golden amber, while the set-backs are carried in lavender. Here, again, a brilliant lighting effect is adequately framed by quiet, unlighted water. Thus the scale and balance of daytime are maintained at night while new colors are introduced.

# THE CAMBODIAN TOWERS AND EAST FACADE

WILLIAM G. MERCHANT, Architect

THE ENTIRE East Facade (to the right but not shown) is lighted in uncolored light in much the same manner as the West Facade. Trenches of 6-ft. width, completely concealed by shrubs and trees, house 500-w. asymmetric floods on 8-ft. centers for lighting walls (Fig. 10); the illumination of the set-back is provided by 200-w. floods. This lighting is broken by large standards at the building entrances and the East Towers and murals (Pl. 6) which form the East entrance to the walled city.

The Towers, rising from tiers of steps, are heavily ornamented in gold leaf and carried in golden light at night. The huge bas-relief gold-leafed murals are lighted by pink fluorescent floods concealed at their bases (Fig. 12), and similar installations light the set-backs in lavender. The terraces and stairs are lighted by Siamese umbrella-type units built of fabric. Trees in the center are floodlighted by 250-w. mercury-vapor lamps (Fig. 8). The lighting of flags and flag masts uses the same installation employed elsewhere (Fig. 9).



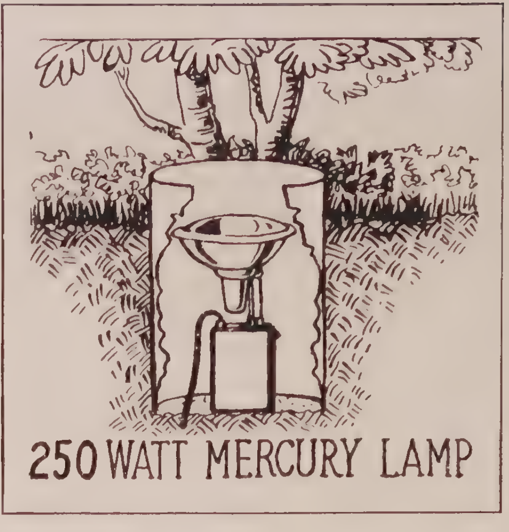


FIGURE 8

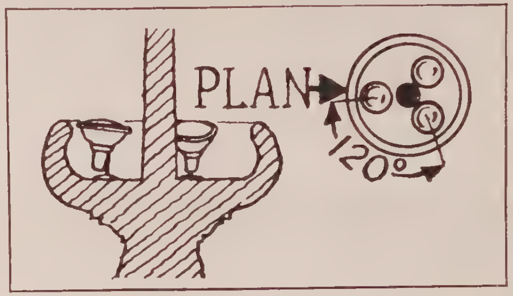


FIGURE 9

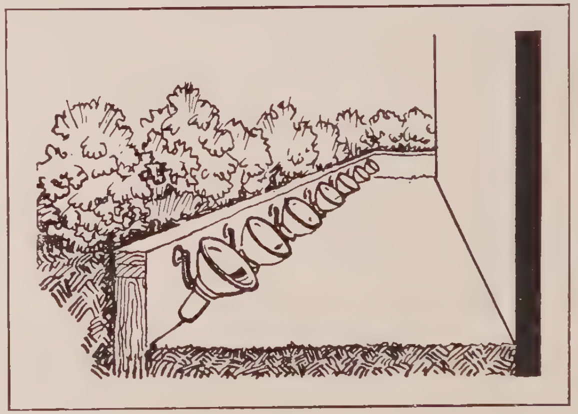


FIGURE 10

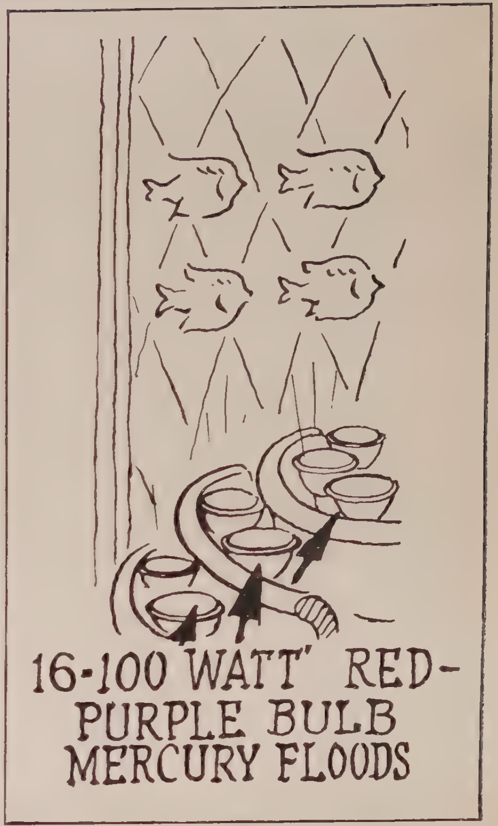


FIGURE 11. Luminescent murals used in the Court of the Seven Seas.

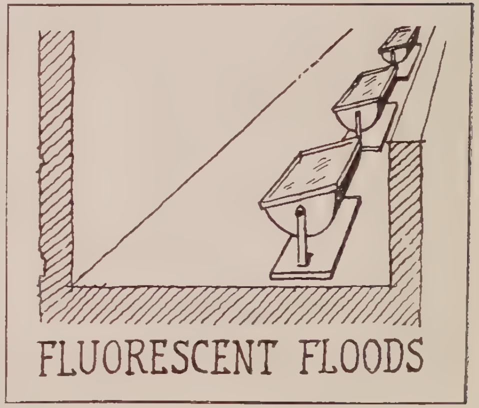
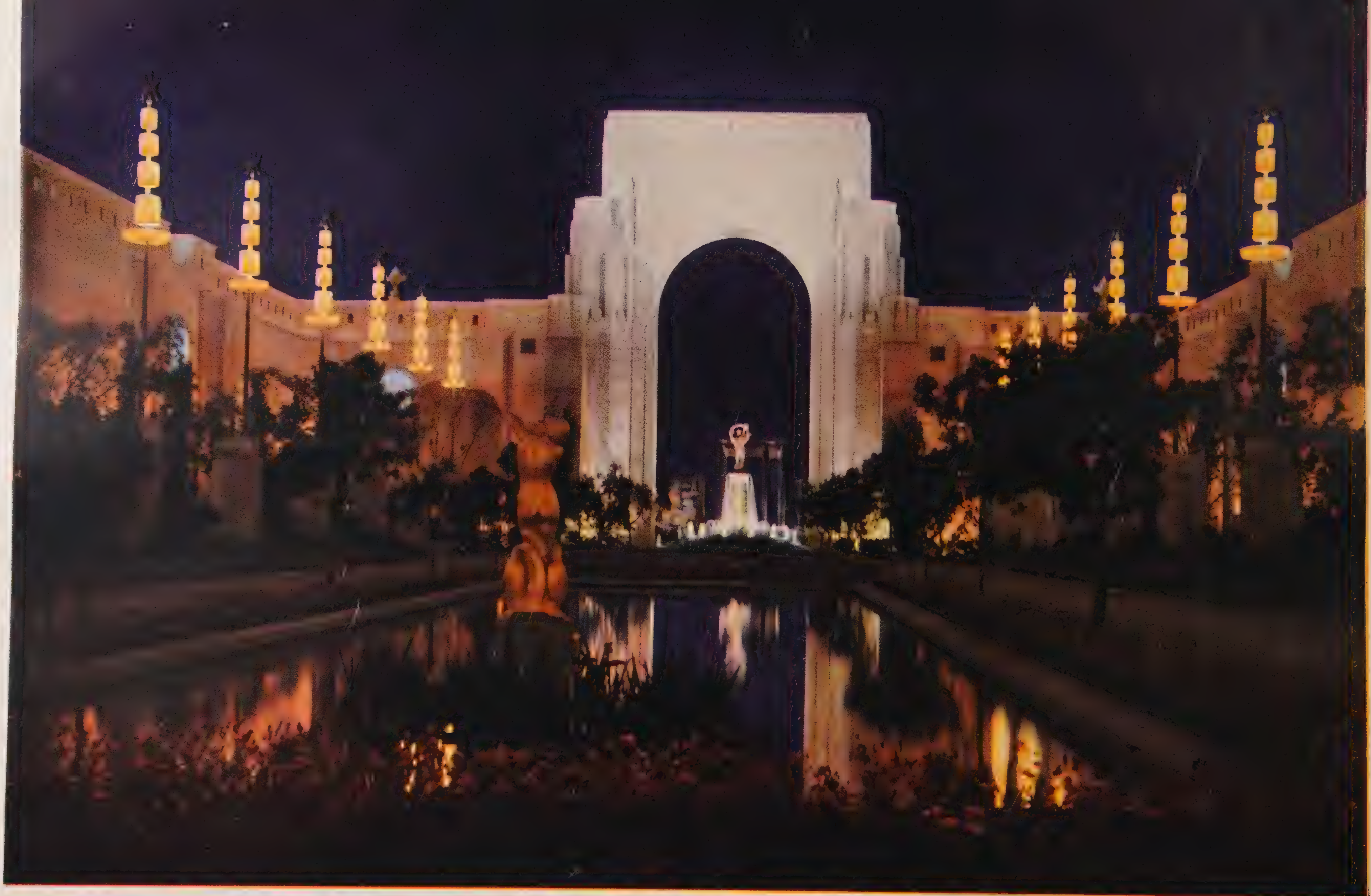


FIGURE 12

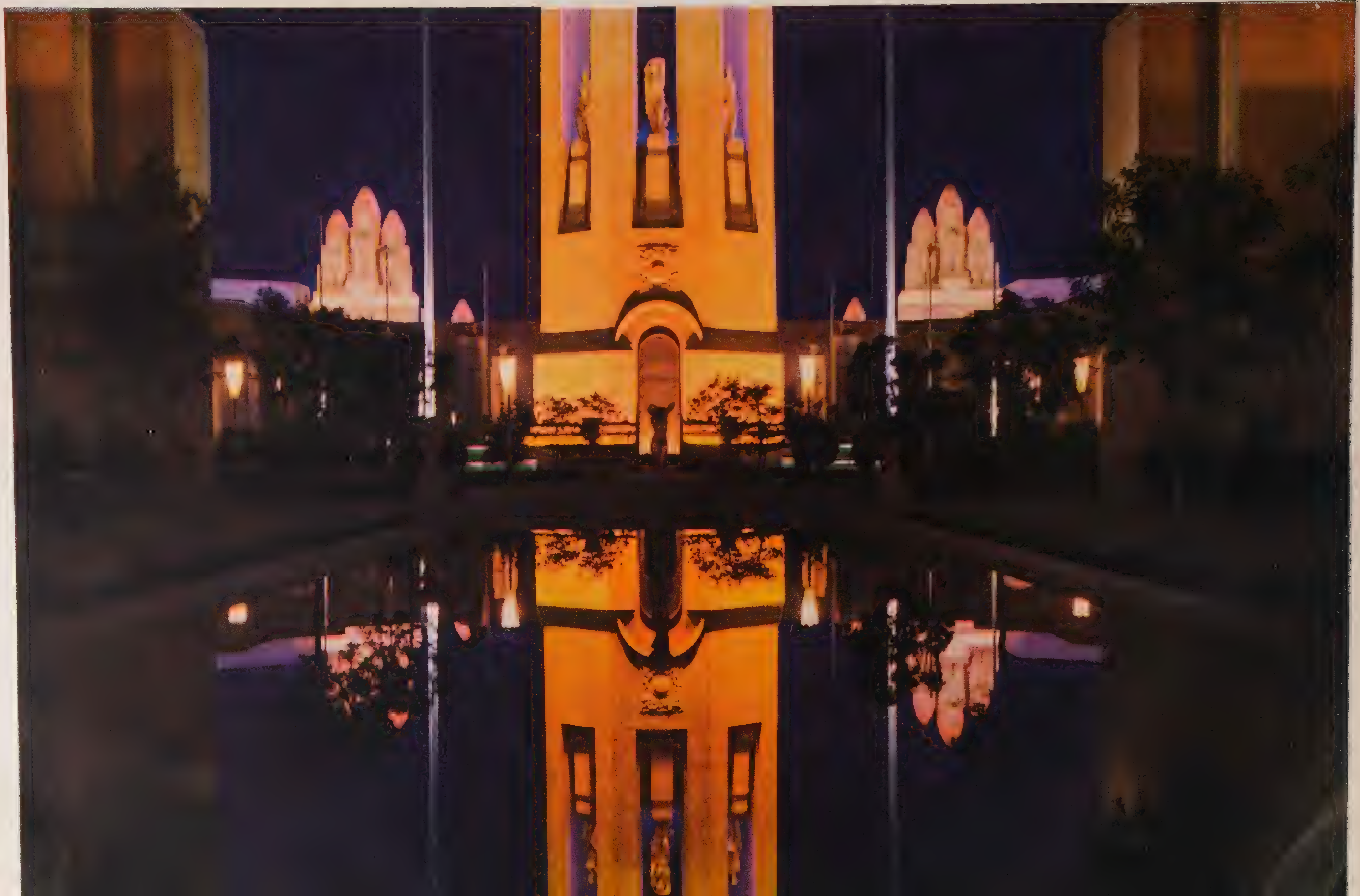


## THE COURT OF REFLECTIONS

LOUIS P. HOBART, Architect

PLATE 7. Connecting the brilliant East Entrance (Pl. 6) and the Tower of the Sun (Pl. 11), the color and lighting levels of this court are adroitly handled. Walls and set-backs are lighted with pink fluorescent floods (Fig. 12), niches with blue fluorescent tubes (Fig. 22). The Arch is flooded from base and adjacent roofs with white 18-in. incandescent searchlights (Fig. 21).

PLATE 8. Looking west in the Court of Reflections towards the Tower of the Sun. As the name implies, water is here used as a reflecting medium to pick up and repeat the brilliantly lit Tower of the Sun. Elsewhere (Pls. 1, 10, and 11) water becomes part of the illumination system itself, adding not only color and movement but a considerable amount of light.



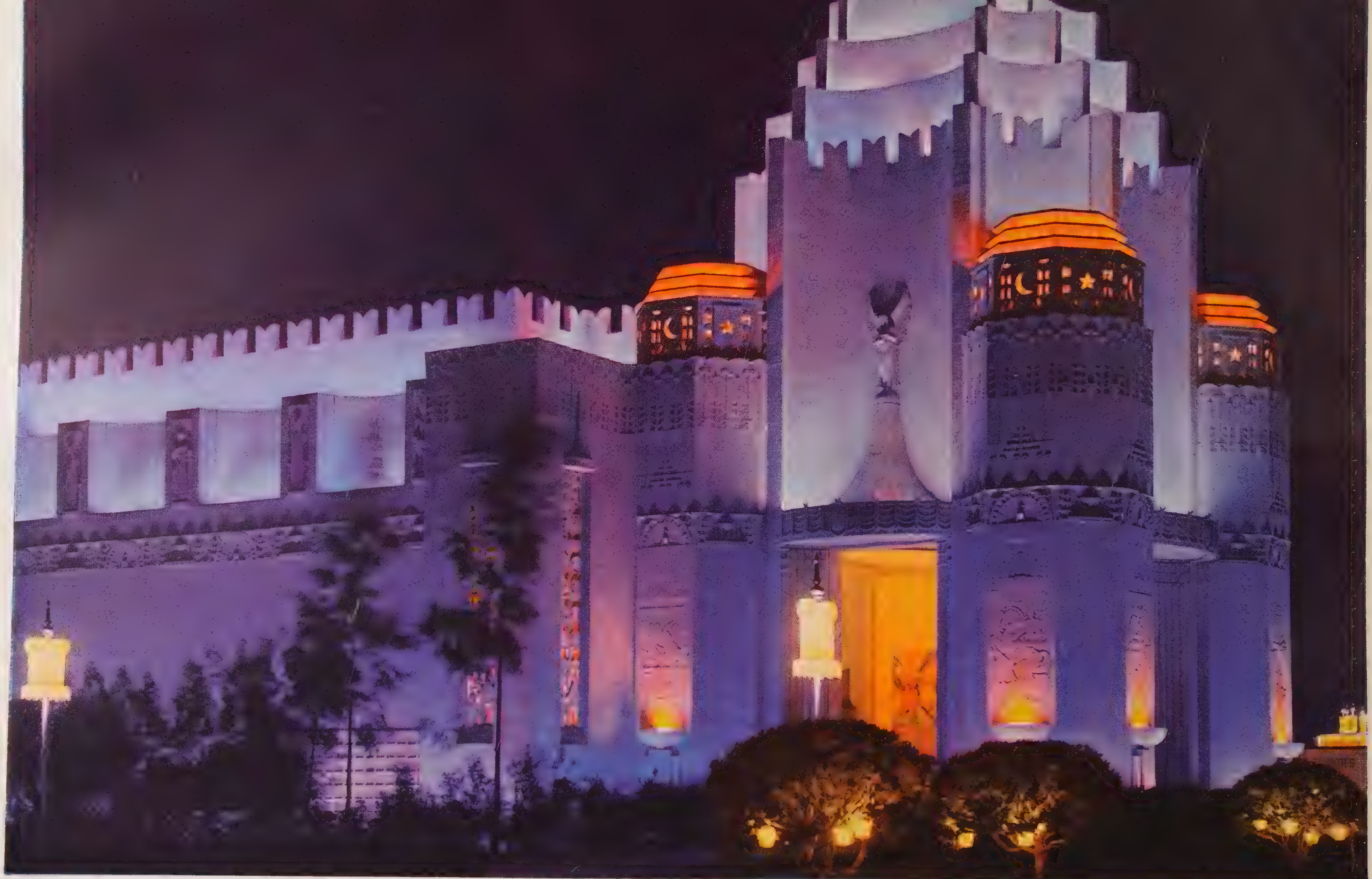


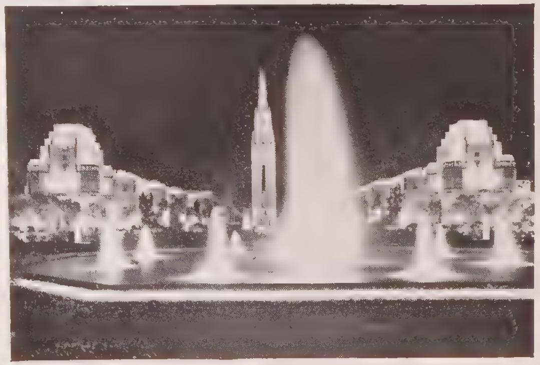
PLATE 9. Illumination of this Court is subdued, employing cool colors and low intensities. The main walls are carried in blue with a lavender overlay, while the set-backs are in blue; a mottled pink-and blue effect is used on the towers. All relief lighting—in grilles, niches, and louvers—is carried in amber to lighten the effect and tie it in with that of the other Courts.

# THE COURT OF THE MOON

## GEORGE W. KELHAM, Architect

HERE, AGAIN, illumination cannily implements both architecture and circulation: although physically one of the four major axes which radiate from the Tower of the Sun, this court is unimportant circulation-wise. The illumination is thus subdued, designed for relaxation, not for pulling heavy traffic. For the walls, 500-w. blue floods are used on 30-in. centers; in the same trench, pink fluorescent floods on 60-in. centers tint the blue to an orchid shade (Fig. 16). The crenelated set-backs are lighted with three 15-w. blue fluorescent floods (Fig. 15). Both blue and pink fluorescent floods are used on the tops of the towers for producing the striking mottled effect (Fig. 14).

Ground lighting is by downlights in ten units concealed in decorative elements of iron and Celoglas (Fig. 17). The other lighting features are: the 24 arches of water, lighted by seventy-two 250-w. amber underwater floods: the north fountain with its falling jets and cascades in amber (Fig. 13); mercury lighted trees: spot-lighted statuary; grilles and turrets in amber relief lighting.



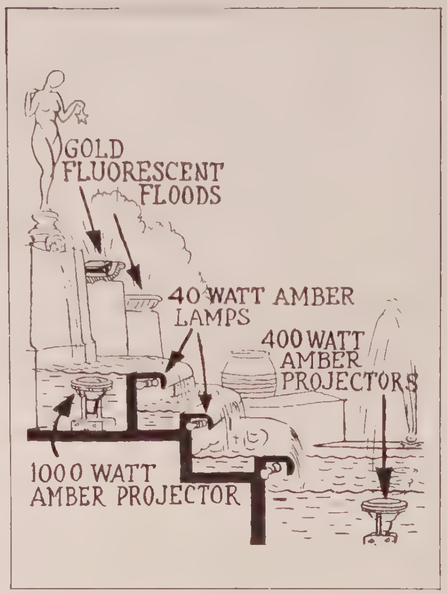


FIGURE 13

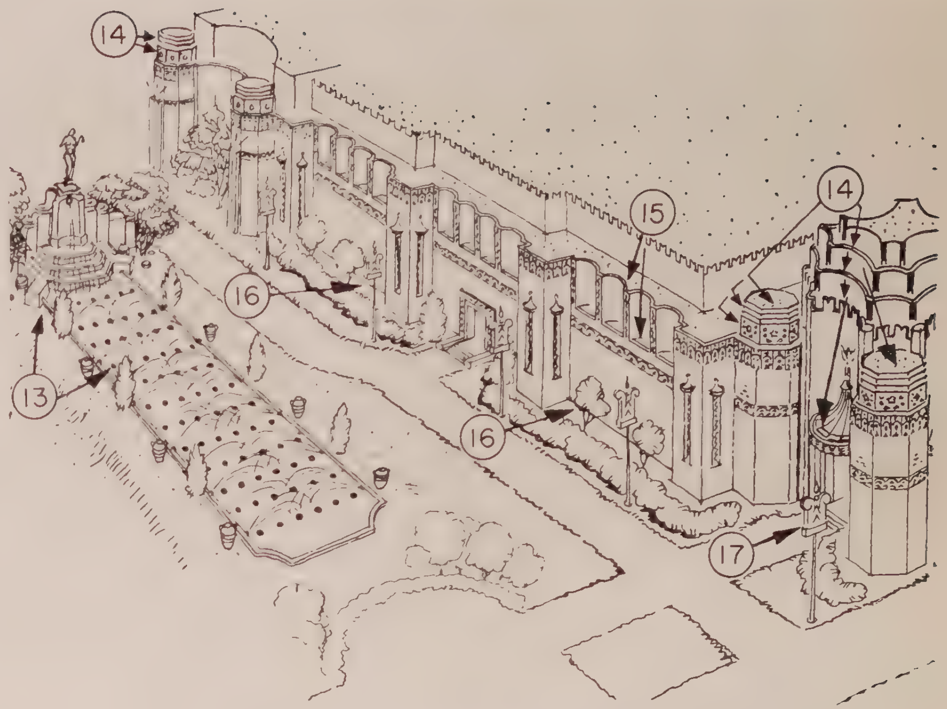


Diagram showing relationship of major installations in Court of the Moon

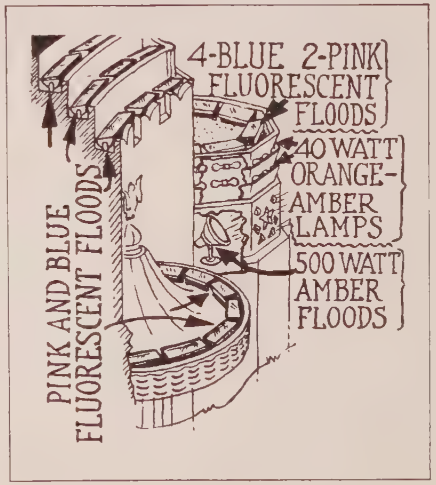


FIGURE 14

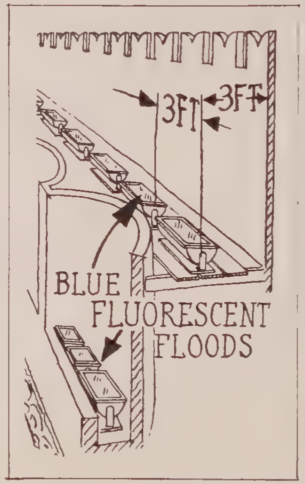


FIGURE 15

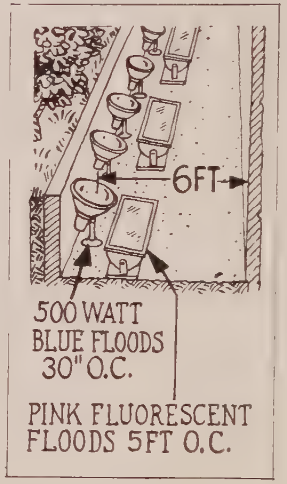


FIGURE 16

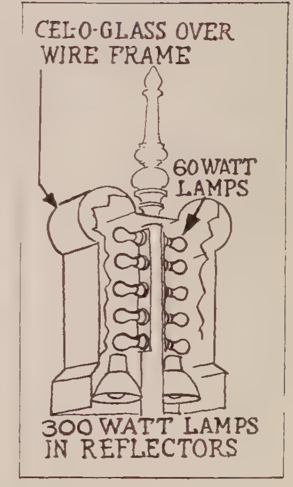


FIGURE 17

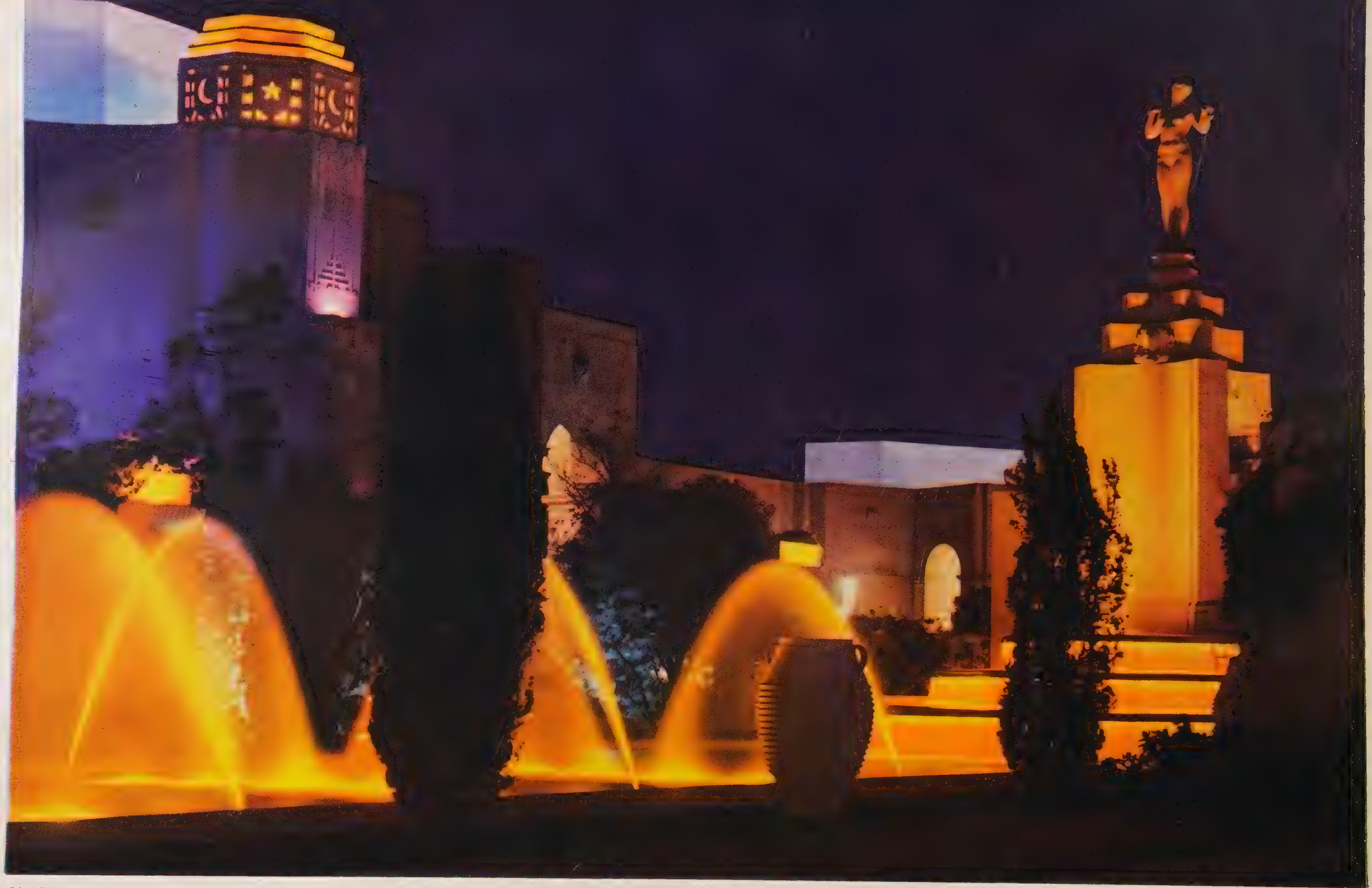
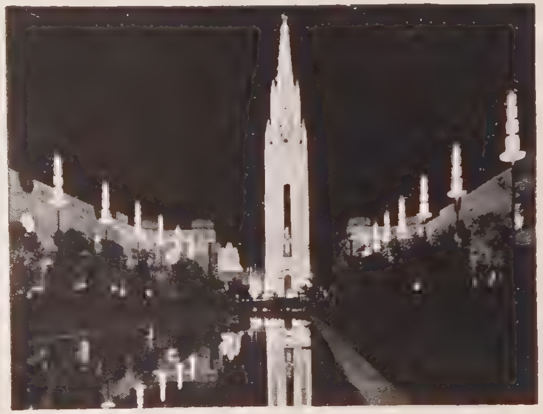


PLATE 10. The golden-amber floodlighting on both Cadorin's sculpture, "Evening Star" and the long pool save the lighting of the Court of the Moon from appearing too low or subdued in key — the 24 jets and the fountain itself give movement to the scene. Added color is achieved by the mercury-lit trees and the relief lighting in amber.

# THE TOWER OF THE SUN

## ARTHUR BROWN, JR., Architect

Since the Tower of the Sun is the "theme center" of the Exposition, and since the Court of Honor in which it stands is consequently the most important traffic intersection within the Exposition gates, it was important that the night effect be at least as dramatic as that of daytime. This has been accomplished (Pl. 11) by concentrating light at high intensities on the Tower, which in turn lights the Court by reflection. The shaft proper is lighted by 56 white 1500 w. searchlights (Fig. 21), 24 amber and 24 white 1000 w. floodlights, and 60 amber 1000 w. floodlights (Fig. 20). A ring of twenty-four 500 w. concealed street-lighting units (Fig. 23) supplements the court lighting. Other features are: the four illuminated fountains (Fig. 1), the eight flags (Fig. 9), the four belvederes and the lighted trees (Fig. 8).



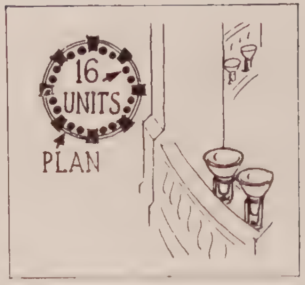


FIGURE 18

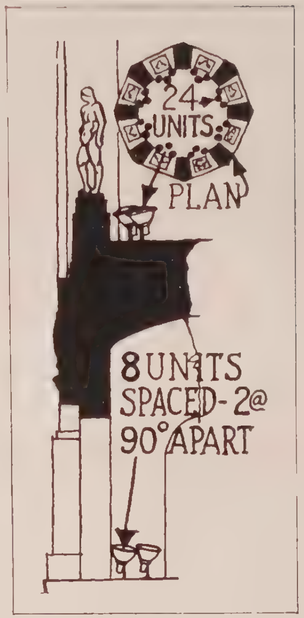


FIGURE 19

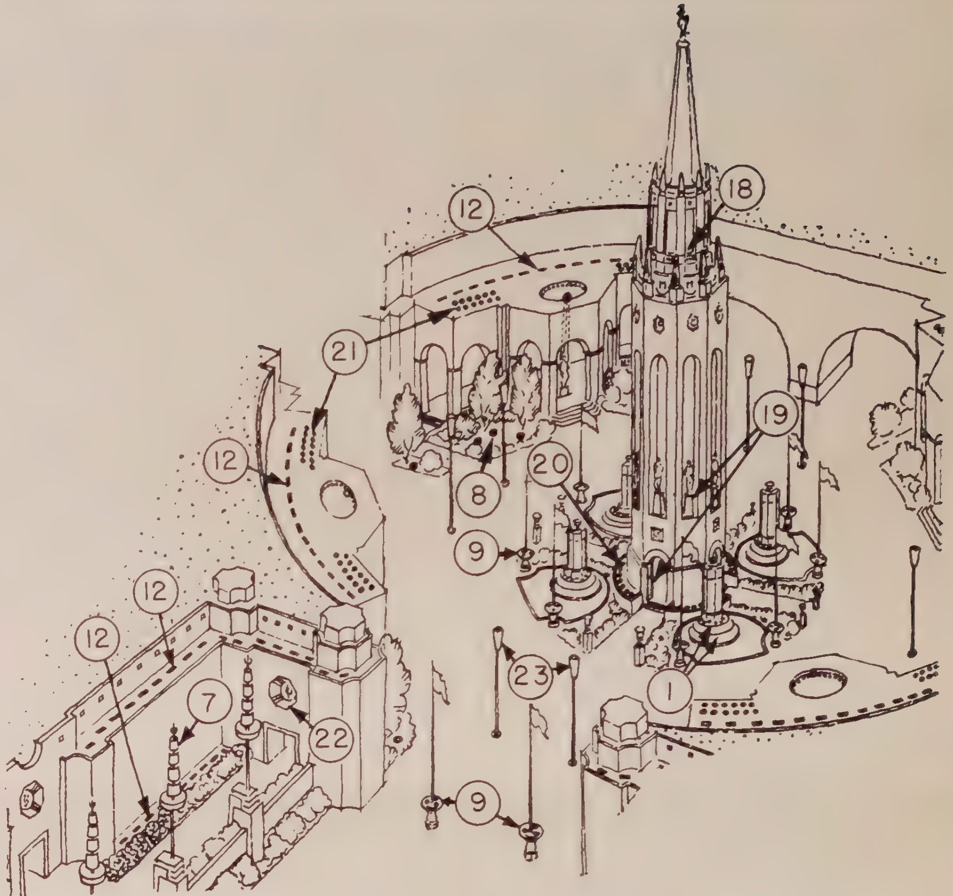


Diagram of all installations in Court of Honor and Tower of the Sun

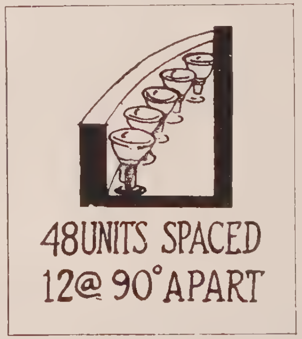


FIGURE 20

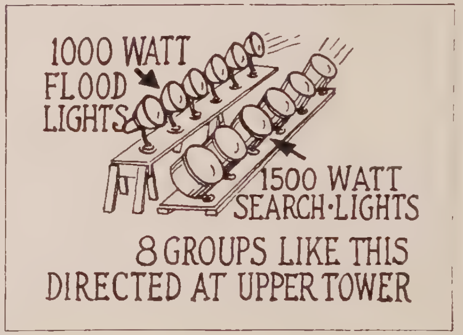


FIGURE 21

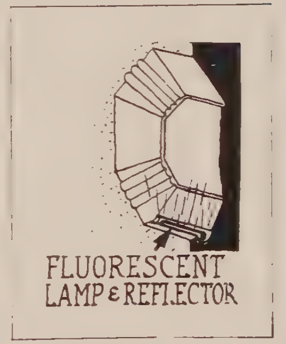


FIGURE 22

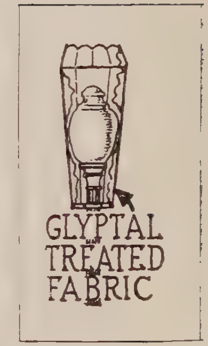


FIGURE 23

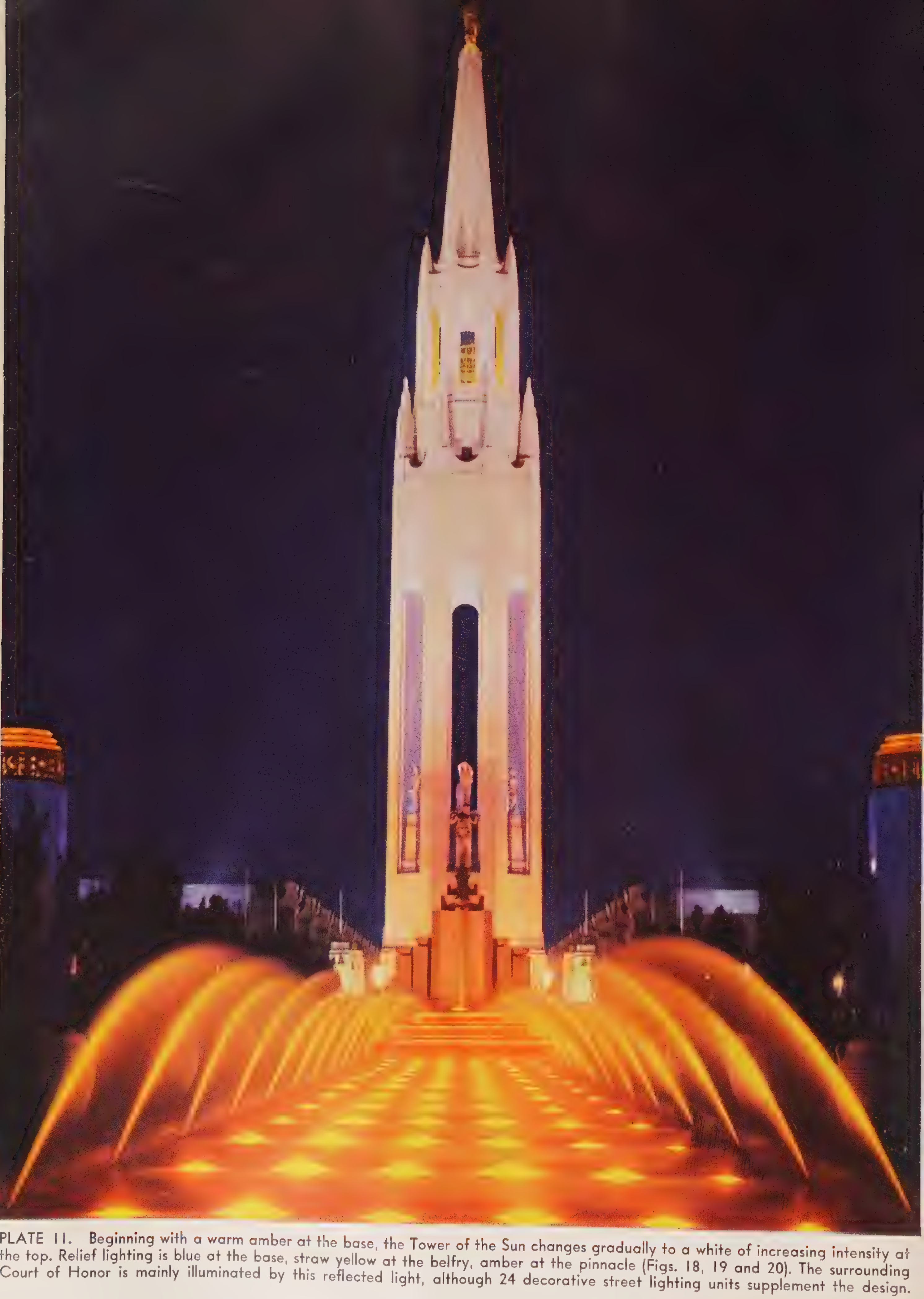


PLATE 11. Beginning with a warm amber at the base, the Tower of the Sun changes gradually to a white of increasing intensity at the top. Relief lighting is blue at the base, straw yellow at the belfry, amber at the pinnacle (Figs. 18, 19 and 20). The surrounding Court of Honor is mainly illuminated by this reflected light, although 24 decorative street lighting units supplement the design.

# Elihu Thomson: Electrical Engineer

The "partially direct and partially indirect but ineradicable influence on electrical engineering" left by the first Edison Medalist is here surveyed by the 1938 recipient of that award.

DUGALD C. JACKSON
FELLOW AIEE

PEOPLE love to say that brilliant achievements belong to the early decades of maturity in men, and that brilliant attainments thereafter are foregone. However, whatever of truth there may be in the saying for men of moderate capacity, the latter part of it does not appear to be valid for men of unusual creative force. Elihu Thomson was one of the latter. His creative mind was forging achievements while he was in his early twenties and it continued in that manner of activity until near the illness which culminated in his death close to the end of his eighty-fourth year. Those were some sixty years of achievement. His major attention during that long period was on electrical engineering. He made an impress on that branch of engineering which has been matched by very few.

Doctor Karl T. Compton has called Thomson an American Faraday; and, indeed, the mental qualities of these two men had much in common, although their tastes were in contrast. Whatever it is which determines a man's tastes, it is not wholly the environment either of youth or of maturity. Some peculiar combination of genes must have final influence. Faraday had many opportunities to turn from the cloisters of independent research but found his fascination in those cloisters. Thomson had opportunity to reside in the cloisters, but his fascination lay in the applications of science to men's purposes. Both of these great men started in chemistry. Both turned to the field of electromagnetism. Faraday made great achievements therein, including the signal discovery of electromagnetic induction. Thomson was prolific in inventions embracing the field of electrical engineering, in the range from individual devices to the foundations of an important special industry. Each turned to other attractions in science as age came on him.

Those who are ardent supporters of the influence of environment on any man's life may speculate on the question of whether, had Thomson worked in the intellectual and physical surroundings of the first third of the 19th century and Faraday in those of the last quarter of that century, their roles might have been reversed. However, this question is outside of my sphere here. It is for us to here consider Thomson's achievements in electrical engineering as they occurred in the last third of the 19th century and the first third of the 20th.*

I have reflected a good deal regarding Thomson's life and I am convinced that he did the things that he did because he liked to do them. I believe that Thomson was as sensitive to, and enjoyed, appreciation as highly as any man. Nevertheless, he did his work, neither for praise, nor for honors, nor for wealth, but primarily because it was of intellectual fascination to him. That was an ideal attitude for commencing a great career of creative invention when Thomson came into electrical engineering, which then was a field mostly covered with thickets of the partly known and a jungle of the unknown. Ampere, Faraday, and Maxwell had made some clearings with major strokes of investigation. Many inventors had followed on, with the endeavor to apply the master discoveries to useful purposes; but the strokes of most of these inventors were feeble. Thomson and a few other giants came in with bold strokes. Thomson thereby established for himself a place as one of those giants in applied electricity who brought to us our modern achievements in the serviceable and comforting uses of electricity and electrical apparatus.

Born in Manchester, England, in 1853, he was still a child when he came to this country with his parents who

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Address delivered at the Thomson memorial meeting of the American Philosophical Society, Philadelphia, Pa., February 16, 1939.

Past-president Dugald C. Jackson is professor emeritus of electrical engineering, Massachusetts Institute of Technology, Cambridge. Much has appeared in recent issues concerning his activities and achievements, including a biographical sketch in January (page 50), and an outline of his qualifications for the Edison Medal in February (pages 64–6).

* It is an interesting reflection that Edward Weston, another of the great inventors whose work is a component part of the foundations of electrical engineering, also had a background of chemistry, and Charles F. Brush started his business life as a chemical expert.

settled in Philadelphia. His schooling was in Philadelphia, and he graduated from the Central High School in 1870. Before the end of that year he was appointed assistant professor of chemistry and mechanics in the same school and six years later he was made professor. In the meantime he started upon that independent career of investigation and invention which is at the center of his fame. Edwin J. Houston, nearly nine years older than Thomson, in those days was professor of natural philosophy in the Central High School and also was active in the affairs of the Franklin Institute. His encouragement may have been helpful to Thomson. A number of Thomson's earlier patents relating to electric arc lighting were jointly ascribed to himself and Houston.

It was at the Central High School that Thomson was brought into contact with various experiments of others, and he carried on for himself many experiments in the laboratories of the school and of the Franklin Institute. During this period he made numerous observations that were later drafted into inventions of importance in the electrical-engineering field. One of his first inventions was the dynamo intended to furnish current for electric arc lamps, which was built under his supervision in a small machine shop on Buttonwood Street and the windings of which he made wholly himself. This machine operated all right and proved capable of serving nine arc lamps in series. The outfit was installed in a basement bakery where it had to be operated in an atmosphere of high temperature. Thomson himself acted as operating attendant during a good part of the early period of operation of this pioneer installation, and he enjoyed telling the story of how he protected himself from heat prostration by drinking, somewhat to the horror of his associates, large quantities of ice water. This "bakery machine," as Professor Thomson called it, is now among the exhibits at the National Museum in Washington.

At that time the Brush arc-light system was in commercial use, and other inventors in electrical engineering were struggling with the problem of suitable dynamos to provide arc-light current, but the problems imposed by the instability of the carbon arcs proved baffling to these inventors and none of them succeeded in those days in fully competing with the unique structure invented by Charles F. Brush and put out by the Brush Electric Company of Cleveland, Ohio. Thomson's uncanny sense of the relative fitness of things and his competency in putting together a well-adapted structure resulted in a dynamo which proved its capability for the purpose. Later, modified and fitted with a Thomson automatic brush-shifting regulator and an air-blast device for preventing destructive arcs at the commutator, Thomson's dynamo (shortly after 1880) became an important competitor in the arc-lighting field.

Series arc lighting has long ceased to be an important commercial factor, while other features of Professor Thomson's productive endeavors have steadily grown into wide influence and use in electrical engineering, but I am personally inclined to put forward this invention of the automatically regulated dynamo for arc-lighting service as a most important one for Thomson on account of its influence on his own later work and on the development of his opportunities.

The invention was made when he was still in his twenties; the construction and installation of the first machine were carried through substantially on his own responsibility except for meager financial aid; and there was drawn out from him at this early age an exhibition of those qualities of originality, courage, resourcefulness, far-sighted thinking, and power in experiment which were to prove to be so notably the foundation for his distinguished and productive career. It was the arc-lighting work, also, which led to the formation in 1880 of the American Electric Company with a small factory at New Britain, Conn., with the 27-year-old Professor Thomson as chief technical spirit; and which eventuated in the company's transfer three years later to Lynn, Mass., where its name became the Thomson-Houston Electric Company. At Lynn, Professor Thomson was established under the sympathetic and capable financial and executive management of Charles A. Coffin, and was happily provided with space and funds for a laboratory sufficient to his needs, in which to experiment, investigate, and invent.

He already had found need for automatic means for extinguishing the arc that results from the operation of old-style lightning arrestors attached to outdoor electric arc-lighting circuits and he demonstrated his grasp of principles relating to electric currents by inventing the "magnetic blowout." Thomson first applied it to lightning arrestors but later also applied it to many other types of devices, and now the magnetic blowout has become so commonplace an incident in electrical-engineering equipment that we often forget that Thomson found occasion to invent it from the whole cloth which was woven out of scientific principles.

In Thomson's early days, electrical engineering was a wilderness of the unknown or the little known for both engineering and science. It has grown to its present great structure of engineering interwoven with exact science as a consequence of the resourceful intellectual work of Elihu Thomson and his peers. Most of the designing and constructing of electrical machines and other apparatus in those early days was by rule-of-thumb and by keen application of intelligence to foresee the probable effects of modifications; in which latter Thomson held a mastery because of his acute powers of observation and his logical powers of mind. As his long-time assistant and colleague, Edwin W. Rice, Jr., said at Thomson's eightieth-birthday celebration, "Throughout his whole career Professor Thomson has exhibited an unerring capacity for the selection of that process which was soundest and best, and simplicity and directness always characterized his designs." And again, "He seems to possess an intuitive insight into nature, and her ways; probably because of the quickness and accuracy of his perception, combined with the depth and range of scientific knowledge, helped by a remarkably retentive memory."

Thomson's intellectual fertility and the scope of his ambition were not of common quality and did not rest satisfied with the arc-light situation, although it was his initiative and originality which had enabled his company to take a foremost place in that art. Therefore we find him at Lynn soon making a mark in the development of other aspects of electric lighting, and of collateral branches in the electrical-engineering field. He found it irksome to lack reliable electrical measuring instruments and he designed his own instruments, with the result that he soon had reasonably accurate standards of resistance and reasonably accurate devices for measuring electric current, voltage, and power. In a short time, his company was manufacturing electrical measuring instruments to go along with its electric-lighting apparatus.

Incandescent lighting with the lamps in parallel on low-voltage circuits, with which we now are so familiar, was coming gradually into a place of importance, but there was no convenient and reliable form of integrating wattmeter to record the consumers' consumptions of watt-hours. Edison had produced a form of meter which recorded by electrolytic deposition, but that type was only serviceable in localities where a moderate chemical laboratory equipped with accurate weighing balances could be set up, and at the best was inconvenient and not very satisfactory. The problem was pressed on Professor Thomson's attention to the point of weariness until, by 1889, he had produced the typical standard integrating wattmeter that for so long has been known as the Thomson integrating wattmeter for direct currents, although it also is available for alternating currents. This was another pioneer milestone in the direction of the development of electrical engineering. Thomson's later inventions of integrating meters intended exclusively for alternating currents also came into importance. Along with the main conception of the first Thomson integrating meter went several lesser features, like the silver contacts at the commutator, which contributed to its perfection when in use.

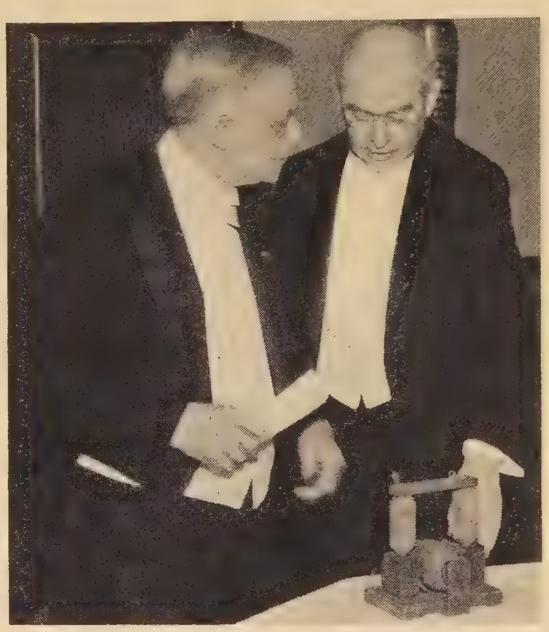
That d-c integrating wattmeter was born when many people were crying for reliable customers' watt-hour meters and some were trying to produce a satisfactory embodiment. But until Thomson directed his mind to the problem, none had succeeded in visualizing the mechanical arrangement of parts or the electrical association of circuits that would give the desired result. Again Thomson's capable grasp of the principles of electromagnetism and of electric circuits as far as then known and his straightforward mental processes gave him the specific conception which produced the result when embodied as a physical device. As in the case of the magnetic-blowout device, it has seemed to me that a formulation of the scientific conception which steps aside from known arrangements, rather than an arrangement of parts, constituted the invention. Possessing the scientific conception, it was easy to form and interrelate the physical parts needed to produce an embodiment. This aspect of the process of inventing partakes of the qualities of scientific discovery in addition to the conventional qualities usually ascribed to invention, and it is of a much higher order than the character of invention which is satisfied with usefully modifying arrangements of parts. Thomson's life shone continuously with the light of this higher order of scientific discovery and invention.

The patent for Thomson's integrating wattmeter was declared invalid in England for lack of invention by a judge following the advice of an expert who testified that, possessing a "tip" which was already in the art, he would have known how to produce the meter. It has always seemed to me that the invalidating decision was an error. The expert, an electrical engineer, was a very experienced and capable experimenter, designer, and inventor, far above the level of a man "ordinarily skilled in the art" at the time of Thomson's distinguished conception, and granting that his statement before the court was correct, it is reasonable to believe that (thinking after the event) he underestimated the intellectual effort required for the conception, which lifted it far above the mental caliber of "one ordinarily skilled." This is an illustration of the embarrassment which we all experience when trying to understand past relations and the significance of former achievements, because we have difficulty in laying aside knowledge and prejudices gained from our present-day life. Similar difficulties beset and mislead many people when they essay to appraise achievements in other fields compared with those in the field of their own endeavor.

Electrically operated contact devices and all sorts of ancillary devices for the electrical-engineering field also came out of Thomson's laboratory in those days. But he was early in reaching correct concepts regarding the designing of dynamos and he already had become immersed in the problems of designing and manufacturing generators and motors for use in the commercial production and distribution of electric power. Mr. Edison, that great leader in the invention of electric lamps and electric-power distribution arrangements, held definitely to direct currents; but Thomson (along with others) came to the early realization that alternating currents could be made very serviceable, provided safe means of distributing the currents generated at high voltage could be visualized. Indeed, while still in Philadelphia, Thomson demonstrated the reversibility of the Ruhmkorff induction coil, which apparently satisfied him of the practicability of using transformers with a-c circuits, and an early patent was issued to him for an electrical distribution system using transformers in parallel on the circuits.

However, the safety to customers whose premises might through a fault be invaded by current directly from high-voltage a-c circuits, even when the voltage normally on any customer's premises had been reduced to a moderate figure by means of a transformer, gave Thomson much concern and thought. He became a foremost early proponent of the practice of metallically grounding the secondary or low-voltage circuits leading from a transformer, which is a practice that is still generally followed. He also invented a device for automatically protecting the circuits in case of failure in the insulation of the high-voltage winding of a transformer.

His mind continually ranged over the field of electrical applications and he constantly produced improvements. These seem often to have been the result of brilliant thoughts which led to arrangements so simple and at the same time so effective, when the thoughts had been applied in physical embodiments, that no one without prior knowledge thinks of the intellectual effort that was necessary to be exercised in order to accomplish the ends. He introduced the reactor as a controlling device for a-c circuits. He perfected series arc-lighting practice for a-c circuits by inventing the automatic self-regulating transformer to convert alternating currents of constant voltage into alternating currents of constant amperes. He early proposed the use of oil filling for transformer cases, to provide dielectric support for the solid insulation in a manner which we still follow. He went into fruitful experiments with high-frequency electric currents; other experiments in the X-ray art when the knowledge of X rays was new and obscure; and experiments relating to electric resistance furnaces; all guided by that intellectual perception of scientific interrelations, and of measures of logical reasoning, on which I have previously commented. Professor Thomson's own notable résumé of his long life of experiment, discovery, and invention is to be found in the 50th Anniversary number of ELECTRICAL ENGINEERING, published by the AIEE, May 1934. I will not continue with a general enumeration but will turn to just two more of his contributions of physical nature.



Elihu Thomson with his former pupil and associate, E. W. Rice, Jr., who at the time of his death was honorary chairman of the board, General Electric Company

In connection with alternating currents he pursued a fascinating thread of pioneering experiments with the repulsions produced by certain arrangements of a-c circuits. His paper presented to the AIEE in May 1887, entitled "Novel Phenomena of Alternating Currents," brought world attention to these features of a-c circuits. The phenomena to which he thus called attention, and some applications which he himself made, are now used in innumerable electrical-engineering devices. The path of development is too wide for me to trace here, but this is another instance in which Professor Thomson left a partially direct and partially indirect but ineradicable influence on electrical engineering.

In electric welding by the resistance process, he made the original discovery in Philadelphia in 1877, and this led to a series of inventions beginning in 1886 which, together with the De Meritens arc-welding inventions owned for this country by his company, have been the foundations of a notably useful special industry of widespread application.* (The first electric welding transformer, built in 1886, is pictured with the inventor on page 251.)

Thomson possessed from his early days a sense of the desirability of standardization where standardization is desirable, and also of the desirability of improvement and the introduction of essentially new objectives where change is desirable. His intellectual balance held eminently good between these two tendencies. When the International Electrical Congress and its International Chamber of Delegates were convened in St. Louis in 1904, Professor Thomson was the president. Out of this meeting there arose the International Electrotechnical Commission with Lord Kelvin its first president and Professor Mascart its second president. Professor Thomson was its third president, holding a term from 1908 to 1911. He thereafter always maintained an active interest in the affairs of this organization and exerted a steadying influence on the complex affairs of international standardization in the field of applied electricity.

I cannot leave my topic without tracing briefly Thomson's effect on electrical engineering through the young men who came under his influence directly, and through his own relations with formal electrical-engineering education. His title of professor came from the Central High School of this city of Philadelphia. One of the first young men whom he had associated with him in business was E. W. Rice, Jr., who was first a loyally admiring student of Thomson and then, becoming his assistant in New Britain, participated jointly with Thomson in some of his inventions. Rice, who rose to very high place in electrical engineering, was throughout his life always insistent on his obligation to Thomson and on his wealth of fortune from having been closely associated with his professor.

I have known many others who came into association with Professor Thomson as assistants in the Company's early laboratory at Lynn. Most of them, like Professor Thomson and his old student and colleague Rice, have gone to their great reward and cannot give us their own testimony, but I can say for them how extraordinary was the unanimity of their sense of the intellectual welfare that they derived from their relations with Thomson. Many of these men became contributors of importance in the progress of electrical engineering.

As the affairs of the company became more widespread, Thomson was no longer so intimate with the personnel, but among the younger men who came into intimacy with him and are active contributors in electrical engineering, there appear the same expressions of gratitude for their contacts with Thomson as an advisor and mentor.

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* In recent testimony before the Temporary National Economic Commission, Hon. Conway P. Coe, U.S. Commissioner of Patents, included the fundamental Thomson welding patent among 16 fundamental patents which he selected to illustrate the great influence of patented inventions on the origination and development of important new industries.

Professor Thomson throughout his life continued his interest in the formal processes of education. During more than 40 years he was an active figure in the affairs of the Massachusetts Institute of Technology. He was a non-resident member of the electrical-engineering staff from 1894 to the time of his death, and from time to time lectured on some special topic in electrical engineering, besides frequently holding membership in or the chairmanship of the MIT visiting committee for the electrical-engineering department, and holding membership in the joint committee from MIT and the General Electric Company which was responsible for establishing the co-operative course in electrical engineering at MIT. He was a busy man, but he took a lively interest in these electrical-engineering activities at MIT, which were in addition to his close relations to the institution as a member of its corporation and for a period its acting president. He also cheerfully gave of his time and thought as a visitor or advisor to other educational institutions.

I have not attempted to enumerate in full the achievements of Professor Thomson in electrical engineering and I have spoken little of the honors which came to him in that field; nor have I referred to his lively interest in other scientific fields. Rather have I endeavored to convey to you in a broad way the impress which his works have made in electrical engineering and to give an appreciation of the intellectual quality which underlay all of his important engineering affairs. If I have succeeded in this attempt you will have realization of why the electrical engineers of this country gladly conferred on Professor Thomson the highest honors that are within their powers collectively to bestow: President of the AIEE, Honorary Member thereof, the first conferred Edison Medal, the jointly awarded John Fritz Medal; besides yielding to him their affectionate and friendly admiration. American electrical engineering thus has crowned Thomson formally with its best laurels in recognition of his great and permanent contributions to the advancement of its art. A like attitude of recognition for his works stands out among the electrical engineers of nations abroad.

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# Room Noise at Telephone Locations

D. F. SEACORD
ASSOCIATE AIEE

*Measurement of noise levels in a wide variety of locations provides data that are valuable in the design of telephone plant*

SINCE the degree of satisfaction with which speech is received over a telephone connection depends on the room noise at the point of reception as well as on the physical elements comprising the telephone circuit, a knowledge of room-noise conditions at telephone locations is of considerable interest to the telephone engineer. As a consequence, measurements of room noise have been made from time to time by the Bell System. The earliest measurements, which were made at relatively few locations, were based on subjective methods.

In 1929, a survey of room noise was carried out by the National Electric Light Association and the American Telephone and Telegraph Company in the course of the work of their Joint Subcommittee on Development and Research. While this survey, covering some 250 locations, was considerably broader than any previously made, it was confined largely to the territory in and around New York City. An early type of objective meter was used in addition to subjective methods. Further objective measurements, using measuring equipment meeting the present specifications of the American Standards Association for sound-level meters, were made during 1936 and 1937 at over 600 locations in four cities, in connection with field tests of the new telephone sets.

Late in 1937, the Bell Telephone Laboratories, in conjunction with several of the associated telephone companies, commenced a still broader survey of room noise. This survey has covered a wide range of different types of locations in various types of areas ranging from rural to congested city districts in and around various major cities. Measurements were made under winter conditions at about 900 locations in and around Chicago and Philadelphia; these data were supplemented by summer measurements at about 500 of these locations. In addition, further data were obtained under summer conditions at about 800 locations in the territory in and around Cleveland and New York, including, in the latter area, nearby locations in New Jersey.

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Report presented at the conference on sound, AIEE winter convention, New York, N. Y., January 23, 1939.

D. F. Seacord is an engineer for the Bell Telephone Laboratories, New York, N. Y.

Although analysis of the measurements made at the total of some 2,200 locations during the latest survey has not yet been completed, some of the results of the preliminary analysis may be of interest, particularly with regard to the average and range of room-noise values measured at various types of locations. The results of the measurements made during the winter in the Chicago and Philadelphia areas, which have been analyzed in considerable detail, are used as the basis of this article. With regard to the difference between summer and winter room noise, comparisons between the measurements made at identical locations under summer and winter conditions in the Chicago and Philadelphia areas indicated, on the average, an increase in room noise of the order of two to three decibels for the summer condition, although there is, of course, considerable range in the differences obtained at individual locations.

The measuring equipment, including a 40-decibel loudness-weighting network, conformed to the specifications described in the ASA "Tentative Standards for Sound Level Meters" (Z 24.3–1936). The microphones used were of the moving-coil type, and the meters used read sound level in decibels above reference sound level, that is, $10^{-16}$ watt per square centimeter at 1,000 cycles in a free progressive wave.

In both the Pennsylvania and Illinois surveys typical areas were selected covering the range from congested city districts to rural districts. In any particular area the judgment of the engineer on the job was relied upon to obtain representative locations, which ranged from factories and large stores and offices to small detached residences. At each location 50 instantaneous readings, 25 by each member of a two-man crew, were made of the noise as indicated by the sound-level meter at approximately five-second intervals. The average of the 50 readings is taken as the average noise and the concentration of the individual values near the average (that is, the standard deviation) is computed as a measure of the variability of the data. It is obviously impractical to obtain sufficient data for each type of location in each area to define rigorously the room noise at such locations; sufficient data were obtained, however, so that by combining similar types of locations in the various areas, noise values considered sufficiently accurate for engineering purposes were secured.

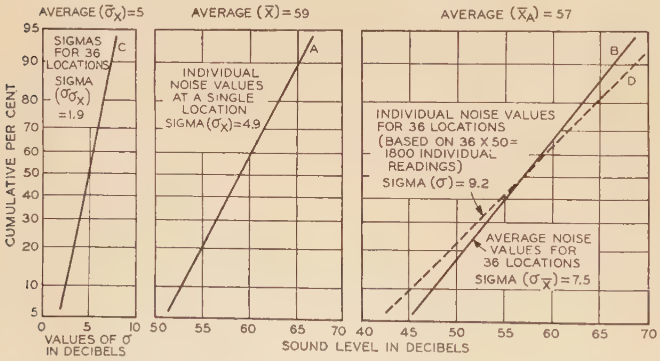


**Figure 1. Distributions of room noise, based on combined data obtained at 36 medium-sized offices (Pennsylvania and Illinois winter surveys)**

Since room noise is a highly variable quantity, it is necessary to express the results of room-noise measurements in such a way that both the average value and the degree of variation involved are described. This may be done graphically by means of distribution curves as illustrated in figure 1. The scale used in this figure, which is known as an arithmetic probability scale, is such that cumulative normal distribution curves appear as straight lines. The data used for this illustration are based on measurements of room noise at 36 medium-sized offices (from three to ten desks). Curve *A* in figure 1 represents the distribution of the 50 individual readings taken at a single typical location; for a normal distribution the average value corresponds to the 50-per-cent point of the vertical scale. Similar average values were obtained for each of the 36 locations of this type, and the distribution of these average values is given by curve *B*.

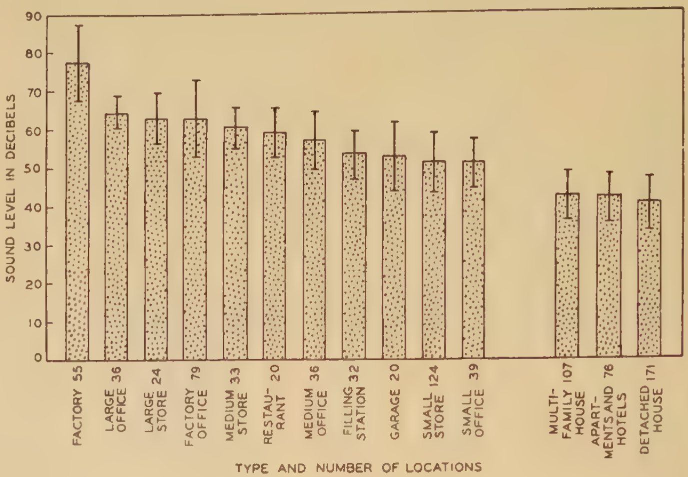


**Figure 2. Room noise by types of locations (combined data from Pennsylvania and Illinois winter surveys)**

Curves of the types shown on figure 1 may be expressed numerically in terms of the average value and a value known as the standard deviation, the latter term being a measure of the spread of a distribution such that approximately 68 per cent of the items have values within the range of plus and minus one standard deviation from the average value. Figure 1 shows that since the character of the noise varies considerably from one location to another, the standard deviations will accordingly vary and cover the range from locations where the noise is fairly constant (low value for the standard deviation) to locations where the noise is highly variable (high value for the standard deviation). The distribution of the standard deviations for the 36 locations is shown as curve *C*. Curve *D* represents the distribution of the 1,800 individual readings (50 at each of 36 locations) and includes, in addition to the variation between the 36 average values indicated by curve *B*, the variation in the readings at each location. The relation between the standard deviation of the over-all distribution (curve *D*) and the separate standard deviations indicated on figure 1 is given by the formula

$$\sigma = \sqrt{(\bar{\sigma}_x)^2 + (\bar{\sigma}_x)^2 + (\sigma_{\sigma_x})^2}$$

With the average values and standard deviations of individual readings available for each location, the data have been combined, using the methods illustrated by the preceding discussion, to include results at a given type of location for all the areas measured in both the Pennsylvania and Illinois surveys. The results of such a combination of data are shown in figure 2, which covers 852 locations, of 14 types (11 business and 3 residence) for which data were obtained at a minimum of 20 locations per type. The height of the bars shown in this figure represents the average value of room noise for the number of locations indicated in the bar, and the single line extension above and below the top of the bar represents the range covered by plus and minus one standard deviation. The numbers shown represent the number of locations of each type measured and are not to be taken as representative of the relative distribution of such types of locations in the plant, as in some cases, such as factories and factory offices, for example, a relatively large number of locations were measured because of the wide variation in conditions.

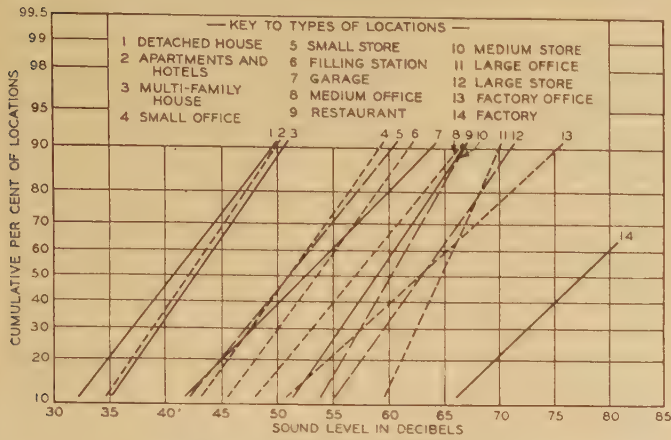


**Figure 3. Distributions of room noise at 14 types of locations (combined data from Pennsylvania and Illinois winter surveys)**

The data shown in figure 2 are also shown in the form of cumulative distribution curves on figure 3. In this case arithmetic probability paper is used, on which straight lines represent cumulative normal distribution curves. The lines shown represent the normal curves which fit the data as obtained from the computed averages and standard deviations, and are distributions of the type indicated by curve *B* on figure 1. It is obvious that the data may be segregated into three reasonably distinct groups covering residence locations, business locations (including factory offices but excluding factories), and factories.

Distribution curves of the data combined on this basis are shown on figure 4. The data used for these curves are slightly different from those included in figures 2 and 3 in that they include seven types of business locations (a total of 48 locations) having less than 20 locations per type, and for residence locations exclude data taken where radios were in operation. Exclusion of the few instances of the latter reduced the average room noise at residence locations by about one decibel. In figure 4 the data for each of the three classes (residence, business, and factory) are plotted separately for the results of the Pennsylvania and Illinois surveys in five-decibel steps. In each case the points shown indicate the cumulative percentage of locations having measured average noise values less than the values given; the straight lines are normal distributions which the actual distributions approximate. These curves, incidentally, closely check the normal distribution curves which would be obtained from the computed averages and standard deviations of the data. For residence and also for business data, a single curve represents closely the distributions obtained from both Pennsylvania and Illinois. The Pennsylvania factory-noise data, however, is materially higher than the corresponding Illinois data, possibly because of different types of manufacturing establishments in the random selection of locations in the two states.

In summarizing the results of the survey of room noise at telephone locations, it is desirable to emphasize again the variable nature of room noise. For example, the average noise values typical of different types of locations vary from about 40 decibels at residential locations to about 80 decibels at factories. Moreover, for a particular type of location the noise is by no means constant from one location to another; five per cent of the residences had average noise levels about 50 decibels, while another five per cent were lower than about 30 decibels, indicating a total range of over 20 decibels. The noise at some residences approaches in magnitude the average noise at business locations and the noise at some business locations approaches in magnitude the average noise in factories. The noise data obtained in these surveys are being used as a basis for devising methods that will reflect more accurately the effects of room noise in the design of telephone plant.

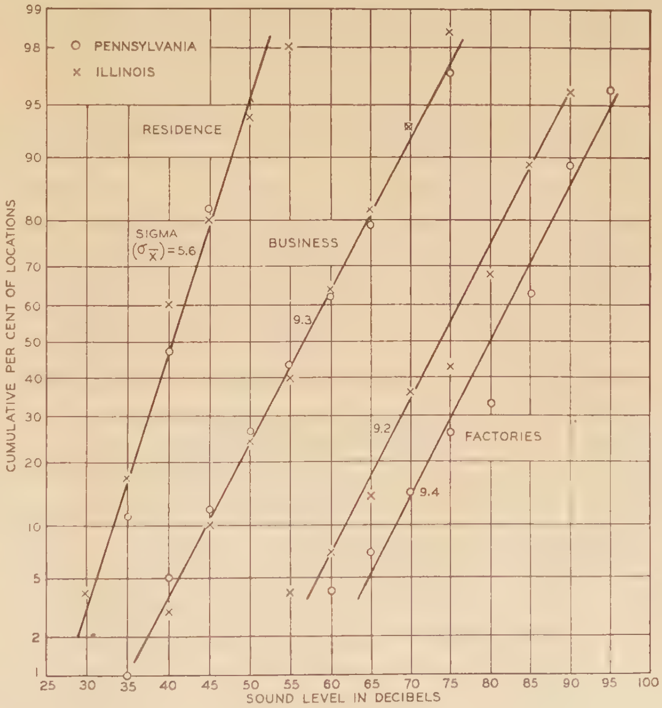


**Figure 4. Comparison of the results of Pennsylvania and Illinois winter surveys on distribution of room noise in residence, business, and factory locations**

# "For Notable Scientific and Industrial Achievement in Electrical Engineering"

## 1938 Faraday Medal of The Institution of Electrical Engineers, Great Britain, presented to W. D. Coolidge at AIEE North Eastern District meeting

THE FARADAY MEDAL, awarded for 1938 to W. D. Coolidge (A'10, M'24), was presented at the AIEE North Eastern District meeting, Springfield, Mass., May 4, 1939, by Gano Dunn (A'91, F'12) honorary secretary for the United States of The Institution of Electrical Engineers of Great Britain. The award was conferred by the council of the IEE at its meeting on January 16, 1939.

Highest honor of the IEE, the Faraday Medal was established in 1921 to commemorate the 50th anniversary of the society's first ordinary meeting. It is awarded not oftener than once a year for notable scientific or industrial achievement in electrical engineering or conspicuous service rendered to the advancement of electrical science, without restriction as to nationality, country of residence, or membership in the society. Seventeenth recipient of the award, Doctor Coolidge is the third American to receive it, the others being AIEE Past-Presidents Elihu Thomson and F. B. Jewett. Nine of the 17 recipients have been members of the AIEE.

W. D. Coolidge is director of the research laboratories of the General Electric Company, Schenectady, N. Y., and one of the world's foremost X-ray scientists. A biographical sketch of him appeared in the March issue (page 137). Full texts of the presentation address by Doctor Dunn and Doctor Coolidge's speech of acceptance follow.

## Careers of Faraday and Coolidge

GANO DUNN, Fellow AIEE

It is unusual, and it increases the honor, when a medal comes to an American from the other side of the Atlantic, for that is evidence of a fame broader than our own national boundaries.

And to a British honor, there is a peculiar character that enhances its value, on account of our common background of political and scientific history, and community of language.

As the local honorary secretary for the United States of America of The Institution of Electrical Engineers of Great Britain, I am authorized by the president and council of the Institution to present the Faraday Medal to Doctor William David Coolidge of Schenectady, N. Y., in consummation of the award made to him on January 16, 1939, for notable scientific and industrial achievement in electrical engineering.

The Faraday Medal has previously been given to only two Americans, Elihu Thomson and Frank B. Jewett.

It is a medal founded in 1921 to commemorate the 50th Anniversary of The Institution of Electrical Engineers, the first ordinary meeting of which, under the name of the Society of Telegraph Engineers, was held in 1871, antedating the AIEE by 13 years.

The Institution of Electrical Engineers has nearly 18,000 members, a considerable number of whom are scattered over the earth throughout the British Dominions. The Faraday Medal is their principal honor, as is the Edison Medal in the AIEE.

In naming it after Michael Faraday, they chose a figure not only high in the world's record of great achievements, but high in the affections of scientists and engineers the world over; on this account the award is without restrictions as regards nationality, country of residence, or membership in the Institution.

### Fascination of Faraday's Life

To every scientist and engineer, there is a fascination in the career of the blacksmith's son apprenticed to a bookbinder, who devoted every moment of his precious leisure to watching the demonstrations of Sir Humphrey Davy from the gallery of the Royal Institution of London, in which, after becoming Sir Humphrey's assistant and then lecturer, he became resident professor, and put the whole world in his debt by his marvelous discoveries.

Faraday is of the type of genius, geometrical rather than mathematical. He asked questions of Nature in the form of experimental presentations devised in the assumption of brilliant working hypotheses, with a flair and a genius for the suspicion of truth long before it became evident. His world was objective and his processes intuitive.

He was the first to infer and later to prove a connection between magnetism and light, and to draw attention to the medium as the seat of phenomena, and he was the first to infer and later to demonstrate not only electromagnetic induction but the possibility of generating electricity from mechanical motion, a discovery on which depends not only the whole power and light industry of today, but so many others that if the discovery were removed, civilization would stop.

A deeply religious man, he left in his character a record as laudable as in his work. I cite these meager facts about Faraday to indicate why The Institution of Electrical Engineers selected him as the exemplar for their principal honor, and why that honor is the highest in their gift to give.

There is for Americans an association with Faraday of which they are proud. It gives to the advent of a Faraday Medal in the United States a measure of sentiment, for it is in part to a distinguished American scientist and administrator that the Royal Institution, which gave Faraday his opportunity and his platform, owes its existence.

### The Roster of Faraday Medalists

| | |
|---|---|
| 1922 | Oliver Heaviside* |
| 1923 | Sir Charles A. Parsons |
| 1924 | S. Z. de Ferranti* |
| 1925 | Sir J. J. Thomson |
| 1926 | Colonel R. E. B. Crompton |
| 1927 | Elihu Thomson* |
| 1928 | Sir J. A. Fleming |
| 1929 | Guido Semenza* |
| 1930 | Lord Rutherford |
| 1931 | C. H. Merz* |
| 1932 | Sir Oliver Lodge |
| 1933 | Sir Frank E. Smith |
| 1934 | F. B. Jewett* |
| 1935 | Sir William Henry Bragg |
| 1936 | André Blondel* |
| 1937 | Sir John Snell* |
| 1938 | W. D. Coolidge* |

* AIEE member

That American was Benjamin Thompson of Rumford Falls, N. H. A member of the Royal Society, he was one of the promoters of the Royal Institution. When ennobled by the Emperor of Austria, he chose the title Count Rumford, under which his experimental determination of the mechanical equivalent of heat and much other valuable scientific work is known.

Benjamin Thompson's part in the founding of the Royal Institution has always been associated in my mind with a reciprocal remarkable gesture of large generosity by a distinguished British scientist, James Smithson, who willed his whole fortune, which was delivered over here in gold coin, to the President of the United States, and certain other officers of the United States Government, eternally to found the great Smithsonian Institution in Washington.

If we are told about the essayist on the life of the Duke of Wellington who gave three-quarters of his space to the great military genius of Napoleon, we must bear in mind that he did it in order the better to display the Duke of Wellington as the world's greatest victor's victor. This is my motive in describing at this length the prestige and honor that lie behind the Faraday Medal.

## Medalist Coolidge's Achievements

It has been awarded to our William David Coolidge of the AIEE (and of so many other scientific and engineering organizations that it is difficult to enumerate them) because of the trail he blazed in the virgin territory of the Roentgen rays (by which name the British still designate what we call X rays) and because of his later great work in that and other fields.

Doctor Coolidge experimented with tungsten for incandescent-lamp filaments and devised the amalgam process for making such filaments.

As far back as 1912 and 1913, he used the results of investigations of Doctor Langmuir in electron emission from hot filaments and produced the Coolidge X-ray tube, which gave complete control of the intensity and penetrating power of the rays, continuous operation without change in intensity, and complete absence of fluorescence of the glass. This tube accommodated voltages up to 200,000 volts, with a corresponding intensity of the rays, and a capacity for revealing new knowledge in widely scattered fields, in which these high voltages were employed for research.

In 1917 Doctor Coolidge brought out a complete portable X-ray generating outfit for military service in the field. This included a specially developed radiator-type tube of large heat capacity which was destined to supplant the earlier type of hot-cathode tube for all diagnostic work.

In 1924 Doctor Coolidge finished developing his oil-immersed self-contained X-ray outfits, which could be safely manipulated without expert technique, and which had many applications in dentistry, in physical laboratories generally, and in industry.

In 1928 Doctor Coolidge determined and explained the cold-cathode effect which limits the voltage that can be used on a given tube. For high voltages he developed a subdivided tube with intermediate tubular electrodes which accelerate the electrons at each stage, so giving an extremely high electron speed for bombardment of the final electrode. He predicted the use of this type of tube working on 2,000,000 volts, which would produce X rays as penetrating as the shortest wave-length gamma rays from radium.

In 1932 Doctor Coolidge presented a remarkable paper at the International Electrical Congress of Paris which put forward the results of his experiments on the "Behavior of Cathode Rays Outside the Generating Tube."

## Recognition Awarded Coolidge

But these are not all his accomplishments. As assistant to Doctor Willis R. Whitney and later as director of research of the General Electric laboratory at Schenectady, N. Y., Doctor Coolidge's work in many fields, including that of ductile tungsten, has been outstanding. It has been recognized by the Edison Medal of the AIEE for his contributions to the incandescent electric-lighting and the X-ray arts, and by numerous other medals; in 1914 the Rumford Medal; in 1926 the Howard N. Potts Medal of the Franklin Institute of Pennsylvania and the Louis Edward Levy Gold Medal; in 1927 the Hughes Medal of the Royal Society of London, and the gold medal of the American College of Radiology; in 1932 the Washington Award of the Western Society of Engineers, and in 1937 the John Scott Medal and Award.

In addition to memberships in numerous scientific societies, he is an honorary member of the Roentgen Ray Society, the American Radium Society, the Radiological Society of North America, the American College of Radiology, the Roentgen Society (of England), the Société de Radiologie Médicale (of France), Nordisk Forening for Medicinisk Radiologi (of Scandanavia); and in 1927 he was awarded honorary degrees of doctor of science by Union College and by Lehigh University.

The Faraday Medal is like the laurel wreath of the

Greeks. It is of bronze rather than of gold, because it was particularly desired that there should be no suggestion of intrinsic value in the medal itself, but that it rather should owe its value, first, to the fact that it was instituted to commemorate the foundation of The Institution of Electrical Engineers, and, second, that it is offered for world-wide service to electrical science and electrical engineering.

In bestowing upon Doctor Coolidge the Faraday Medal, The Institution of Electrical Engineers is placing his name in a roster made illustrious by world-known names, to which roll of honor his name is a worthy addition.

# Modern Developments From Faraday's Work

W. D. COOLIDGE, Member AIEE

I was sorry not to be able to go to England to receive this great honor directly from The Institution of Electrical Engineers. In some ways, however, it is not unfitting that I receive it through the kindly auspices of the AIEE, of which I have long been a member. Nor is it unfitting that I receive it in Springfield, Mass., for there are many factors connecting this locality with the event.

Benjamin Thompson was born in Woburn, Mass., only 86 miles from here, and he it was who, in 1796, formulated a plan which later resulted in the establishment of the Royal Institution in which Michael Faraday found the opportunity for his work.

Only a hundred miles west of here, in Albany, N. Y., another pioneer, Joseph Henry, carried out his early experiments in electromagnetic induction.

Professor Elihu Thomson, an earlier Faraday Medalist, spent many of the most productive years of his life in Lynn, Mass., only a hundred miles east of here. He was one of the most prolific of the pioneers in applying to the generation, utilization, and measurement of the electric current the principles of electromagnetic induction established by Faraday. Furthermore, I am sure it was Professor Thomson's influence, more than that of any other, upon his one-time pupil, later assistant, and, still later, chief, Doctor E. W. Rice, which was responsible for the foundation and active support of our Research Laboratory.

Finally, as one more factor connecting this locality with this event, my own birthplace is only a little over fifty miles from here.

But, if the location suggests geographical relations, the occasion emphasizes their unimportance. This award by a British institution to an American is one more bit of evidence of the fact that science knows no national boundary lines.

## Tribute to Laboratory Associates

It is in a spirit of deep humility, so far as my own contribution is concerned, that I accept the honor conferred upon me by The Institution of Electrical Engineers in giving me this medal and adding my name to the illustrious group of Faraday Medalists who have preceded me. I must accept it not as a personal tribute but rather as a tribute to a splendid group of workers of which, for 33 years, I have been so fortunate as to be a member.

That group was organized by Doctor Willis R. Whitney. By precept and example, he succeeded in bringing about such close co-operation that it is difficult, if not impossible, for me or any other member of that group to point to any development brought to anything like full fruition, which he could call exclusively his own. I take this opportunity to acknowledge the inspiration and generous help which I have received from Doctor Whitney and from my associates.

## The Electrical Industry's Debt to Faraday

And also I feel that I truly owe an acknowledgment to Michael Faraday, for his fundamental researches were an effective stimulus to the conception of our laboratory. Not only can the origin of many General Electric products be traced directly to his work—such as our generators and transformers, which are the engineering derivatives of his classic discovery of electromagnetic induction—but, since economic generation and distribution of electric power have made possible the development of our great electrical industry, it may truly be said that our company owes its existence, as part of that industry, to Faraday's experiments.

It was the clear recognition of that fact by Doctor E. W. Rice and his associates that led to the foundation of our laboratory, in the hope, as Doctor Rice expressed it, that it might result in the establishment of new facts and principles which could serve as the basis for new things to be made in our factories.

As one studies Faraday's work, one is impressed, first, by the magnitude and diversity of the contributions he made to science, and second, by the simple equipment with which he achieved such epoch-making results. When Helmholtz visited him

Faraday Medal being presented to Doctor Coolidge by IEE Honorary Secretary Dunn

toward the close of his life and inspected his laboratory, he wrote in astonishment about the few pieces of copper wire and iron bars which had sufficed for the most far-reaching discoveries.

I think that the director of any modern research laboratory would hate to compare the output of his laboratory per dollar spent for either equipment or salaries with that of Faraday's laboratory in the Royal Institution. He would need several excuses. In the first place he would point out that he had not been able to find many young Faradays for his staff, and in the second place that much of the fundamental research work of today calls for complex and expensive equipment.

Such is the inevitable result of progress in research. In pioneering in a new field, simple tools may suffice, but, with the fundamental principles discovered, further work demands highly specialized facilities, for refined measurement, tests under extreme conditions, and development of special applications.

## Extensions of Faraday's Research

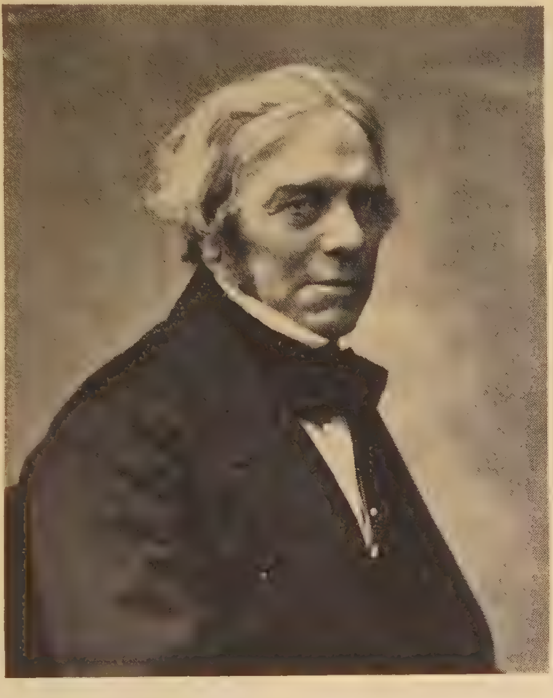
This might be illustrated by many examples, taken from our recent work, of extensions of research along trails first opened by Faraday.

He recognized the need, in electromagnetic apparatus, of copper, insulation, and iron. With reference to the first of these, we have found it necessary to do much metallurgical research on copper. We have learned that we must free it of any oxide along grain boundaries if it is ever to be heated in a reducing atmosphere. Or, if it is to be stressed at elevated temperature, we may have to add silver to raise its equicohesive temperature and so prevent brittle fracture.

For primary insulation it has often been desirable first to enamel wire and then to wrap it with cotton or silk. Recent work has resulted in an enamel derived from polymerized vinyl acetate which is so adherent and so elastic that no other covering is needed, and so the space-factor is improved.

For secondary liquid insulation, non-inflammable pyranol has been developed, to be used in place of oil.

Recently we have become actively interested in the insulating properties of certain gases, notably the chlorine and fluorine derivatives of the methane hydrocarbon series. In the case of a new million-volt transformer-type X-ray outfit, 100 pounds of one of these compressed gases is furnishing insulation equivalent to that of 12,000 pounds of the liquid oil ordinarily used in transformers.



**Michael Faraday**

Photograph reproduced from *The Telegraphic Journal and Electrical Review*, London, July 15, 1877

Research on transformer steel has been carried on continuously ever since our laboratory was started, and, as a result, magnetic losses have been reduced to less than one-fourth of what they were. Recent work has shown that, through the best amount of cold rolling, long narrow strips of steel may be produced having maximum permeability in the direction of their length, and that these, when preformed and annealed, can be wound around the primary and secondary coils to form the core of a transformer which for the same electrical performance is better mechanically, calls for less hand labor, and is some 40 per cent lighter in weight than its predecessors.

Faraday made many ferrous alloys and studied their physical properties. As ferrous alloys stronger at high temperature would make possible the attainment of higher economies in power production with both the steam and mercury processes, we are making many experimental alloy steels and testing them under sustained load at elevated temperatures. In this work special attention is paid to creep rate and to the determination of the equicohesive temperature range.

Some of our steel work has been in search of alloys having the same heat expansion as special glasses, to permit their being sealed together for the construction of vacuum tubes of various kinds and for other uses.

Much of our alloy work, both ferrous and non-ferrous, has been greatly facilitated by the pressed-powder method, with which we first became acquainted through the development of ductile tungsten and ductile molybdenum, and later carboloy.

Faraday studied the inactive or passive state of iron. We have recently been studying this in connection with the corrosion of stainless steel.

Faraday was interested in permanent magnets, both natural and artificial. We have been quite active in this field and, as a result, have seen the strength of permanent magnets gradually increased during the last 30 years some eight- or tenfold. The latest cast Alnico magnets consist of an alloy so hard that it cannot be machined. This would make the construction of small magnets of this material so expensive as to limit their use appreciably. We have recently found, however, that they can be made just as good, and for certain shapes much more cheaply, from pressed powder.

We are still actively interested in the sparks and arc-discharges with which Faraday worked. Only the dimensions have changed. Our latest 10,000,000-volt impulse generator produces sparks 30 feet long, while another high-current impulse generator delivers a quarter of a million amperes—more current than has ever been measured in a lightning stroke.

Arc characteristics are being studied in various gases and at pressures up to more than a thousand atmospheres. At moderate pressures, arc discharges in neon and in mercury vapor are being studied as light sources, while the low-temperature mercury arc has been coupled with a phosphor to transform the ultraviolet radiation into visible light, and so to increase the light output.

In radio research and in television, we are continuing Faraday's work on electromagnetic action at a distance. The principles are those discovered by him and formularized by Maxwell, but the distances have outgrown both the laboratory and the earth.

Faraday's leadership is a never-failing inspiration. To follow in his footsteps is a privilege indeed. To have succeeded in pressing a little farther along the paths he pointed out brings a satisfaction which itself sufficiently rewards the effort.

## European Welding Practice*

WELDING has grown to be as important a tool in engineering in Europe as it is in the United States. Welding machines in Europe are of high quality and in most countries of a-c equipment is far more widely used than d-c equipment. Special attention has been directed to low-rating machines for thin-gauge welding with the consequence that very excellent a-c and rectifier type sets have been developed for this work.

Welding electrodes in Europe are primarily of the shielded-arc type, although considerable quantities of bare and light-dipped electrodes are still in use in Germany and France.

Spot and other types of resistance welding are not in as common use as they are in America. There is great interest in this method, however, particularly for automobile, aircraft, and railway construction. Automobile manufacturers are considering installation of tube-controlled equipment for the production of duraluminum bodies. Gas welding, cutting, and brazing are in common use and very high-grade results are being obtained on all types of metals.

The industries in which welding is being used compare with those in the United States. Ships, buildings, bridges, railway coaches, autos, buses, elevators, pressure vessels, and all engineering equipment are now being fabricated by welding.

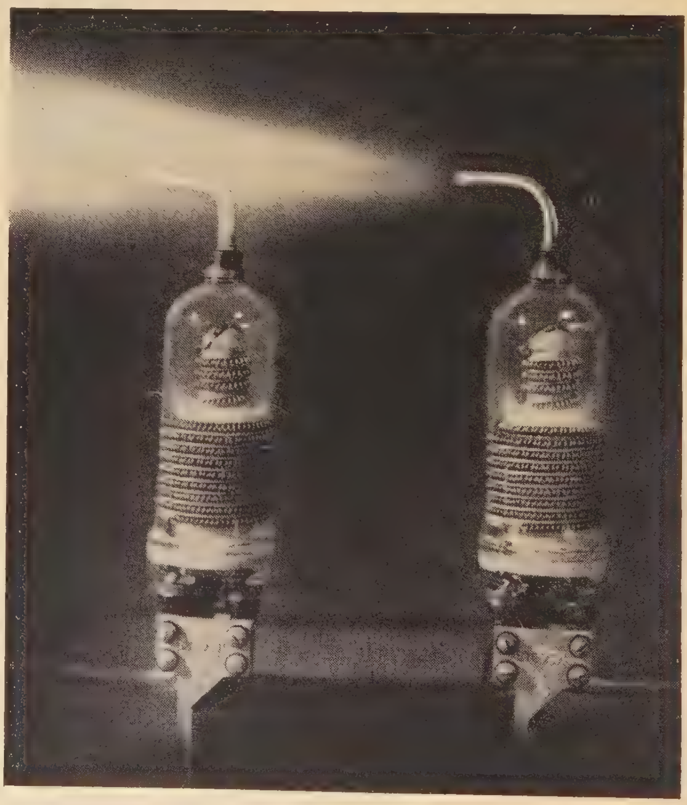
Although welding is now used in nearly every field of engineering, the indications both in Europe and America are that its development in the future will be even greater than in the past.

## Lamp-Size Steam Generator

A STEAM generator no larger than an ordinary incandescent lamp has been developed by the lamp division of Westinghouse Electric and Manufacturing Company. Heating coils of the device are directly immersed in water, providing a thermal efficiency of 90 per cent. It can generate superheated steam from cold water in less than 15 seconds. The heater is made in 1,000-, 1,500-, and 2,000-watt sizes, with evaporating capacities up to 5.7 pounds of water per hour. Steam can be superheated by it to 350 degrees Fahrenheit.

The cylindrical case of the generator is $9^1/_4$ inches long, and is made of transparent chemical-resistant glass, capable of withstanding mechanical stress, internal pressure of 25 pounds per square inch, and instantaneous transfer from cold to boiling water or vice versa. The case is provided at one end with two heavy electrical terminals, welded or sealed directly into the glass, and another threaded pipe is sealed into the opposite end as a steam outlet. Resistance wire coiled on an insulating core occupies most of the interior, leaving space for only five ounces of water at a time.

The steam generated by the device can be used to sterilize dishes, glassware, instruments, utensils; or for pressure cookers, chemical laboratories, small-scale industrial operations. The generator can also be used to produce small supplies of distilled water for drinking, medicinal purposes, or garage use, and to provide hot water for ordinary domestic uses. It operates on an ordinary electric circuit. The accompanying illustration shows two of the small generators.



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*Abstract of an address delivered by C. H. Jennings, engineer in charge of welding research, Westinghouse Electric and Manufacturing Company, at the annual convention of the Association of Iron and Steel Engineers, Cleveland, Ohio, September 27, 1938.

# News
## Of Institute and Related Activities

# South West District Holds Successful Meeting

A VERY successful three-day meeting and Student Branch convention of the South West District was held in Houston, Tex., April 17–19, with headquarters in the Rice Hotel. Over 500 members, guests, and students attended and took part in the various activities arranged by the committees, such as technical sessions, inspection trips, and social functions. The subject of oil-field operations was treated by papers presented in three of the nine technical sessions. One of the high spots of the meeting was a talk on "Geophysical Prospecting," by L. W. Blau, of the Humble Oil and Refining Company, Houston. The meeting was opened at 10:00 a.m. Monday, April 17, by F. C. Bolton, vice-president, South West District AIEE. The address of welcome was given by H. O. Clarke, Jr., vice-president, Houston Lighting and Power Company.

### JOINT LUNCHEON WITH HOUSTON ENGINEERS CLUB

Tuesday noon a joint luncheon with the Houston Engineers Club was held in the ballroom of the Rice Hotel, at which John C. Parker, president, AIEE, was the principal speaker. Doctor Parker spoke of the broader aspects of the engineering profession and its relation to society.

Illustrating how modern civilization depends on the work of the engineer Doctor Parker referred to the alarm clock and the precision chronographic instruments, food cooking and preservation, the communication of intelligence, the radio, and talking motion pictures. On the other hand he spoke of the engineer as a product of civilization, citing that modern hydraulics owes much to the work of Leonardo da Vinci. Clerk Maxwell's work about three-quarters of a century ago provided a foundation for radio, and his experiments in flame work and combustion were vital to the petroleum industry. The opportunity that exists in the United States for the most advanced education at the lowest possible cost, is a result of the background of centuries of civilization. The dedication by the public of certain rights makes possible public utility enterprises, highways, bridges, and other works. Legislation gives engineers an opportunity to pursue their profession and earn a living, but resolutions and legislation cannot accomplish everything. He referred to the high code of ethics and traditional honesty of the engineering profession, and suggested that, if engineers would take back into their communities the factual methods of approach used in their work, they would contribute much of value to community life.

J. B. Dannenbaum, president of the Houston Engineers Club, presided at the luncheon. President Parker was introduced by District Vice-President Bolton.

### SOCIAL EVENTS AND ENTERTAINMENT

Over 300 attended the chief social event of the meeting, a dinner-dance held in the main ballroom of the Rice Hotel. A musical program of songs and dancing was presented by the Mary Jane Reynolds Dancing School.

On Monday evening a large number of members and guests attended a stag supper held at the Gulf Brewing Company, 5301 Polk Avenue.

### INSPECTION TRIPS

Monday afternoon 332 members and students took part in three parallel inspection trips. First in popularity was a trip to the Deepwater Plant and the Champion Paper Company, both located on the ship channel, about 11 miles from meeting headquarters. The second was a trip to the Turning Basin and to radio stations KTRH and KPRC, which transmit simultaneously on the same antenna using different frequencies. This trip also included the San Jacinto Battleground and the new monument there. The third trip was an inspection of the local and toll offices of the Southwestern Bell Telephone Company and the underground networks of the Houston Lighting and Power Company. The trips were arranged by the transportation and inspection committee: L. K. Del'Homme, *chairman;* L. B. Bricker, J. M. Craddock, W. C. Geirisch, G. R. Swindell, and H. C. Taylor.

### DISTRICT EXECUTIVE COMMITTEE MEETING

On Tuesday, April 18, a breakfast meeting of the District executive committee of the South West District was held in Banquet Room B of the Rice Hotel. The committee adopted a resolution to support the St. Louis Section in its request to hold the next meeting of the District in St. Louis. President Parker complimented the Houston Section for its work in connection with the District meeting and praised the District for its very active Sections and Branches. He reported the Institute to be in excellent condition financially, with growth more rapid than the rise of the general business index. Emphasizing the importance of keeping in contact with young engineers, President Parker suggested placing young men on Section and District committees, and recommending young men to headquarters for appointment on national committees. H. H. Henline, national secretary, discussed the growth of the Institute since 1902, when it had 1,550 members, to its present 67 Sections and 120 Student Branches, with nearly all members in the United States having Section affiliation. The last four Sections were created in areas formerly assigned to other Sections and plans are being developed for a new Section at El Paso, Texas. In regard to finances he said that some of the reserves were used in the depression period but they have been restored and there has been no reduction in essential Institute activities. He informed the committee that in some Sections subdivisions for specialized programs have been created to meet the needs of specialists.

**Analysis of Registration at Houston Meeting**

| Classification | Houston Section | District 7* | Other Districts | Totals |
|---|---|---|---|---|
| | Location | | | |
| Members | 84 | 107 | 19 | 210 |
| Students | 50 | 73 | | 123 |
| Men guests | 95 | 47 | 9 | 151 |
| Women guests | 20 | 29 | 2 | 51 |
| Totals | 249 | 256 | 30 | 535 |

* Outside of Houston.

Other items of business considered were distribution of information on available speakers, time for installation of Section officers, sending program announcements to other Sections, and membership matters. The committee decided to hold its next meeting early in the autumn at Tulsa, Okla., the exact date to be decided later by the vice-president.

### STUDENT ACTIVITIES

A large number of students and counselors attended a get-together luncheon given by the Houston Lighting and Power Company at Kelley's Restaurant Monday noon. President Parker addressed the gathering.

Wednesday noon the Rice Institute was host to a luncheon conference of Student Branch counselors and Branch chairmen.

During the meeting three student technical sessions were held, which were well attended. The following papers were presented:

INDUCTION MOTOR OPERATION WITH SEPARATELY EXCITED PHASE ADVANCER, D. L. Hall and B. D. Low, The Rice Institute.

FAILURE OF CEMENT-INSERT PORCELAIN INSULATORS, G. M. Lee, Graduate Student, University of Missouri.

APPLICATION OF TENSOR ANALYSIS TO ELECTRICAL

NETWORKS, **R. P. Haviland**, Missouri School of Mines and Metallurgy.

AN A-C NETWORK ANALYZER, **T. E. Acord**, University of Texas.

DIRECTIONAL ANTENNAS FOR BROADCAST STATIONS, **R. B. Bonney**, University of New Mexico.

FIBER GLASS AS AN ELECTRICAL INSULATION, **Leslie Lawrence**, Oklahoma Agricultural and Mechanical College.

THE INVESTIGATION OF PROPELLERS FOR WIND-ELECTRIC PLANTS, **E. P. Smith**, Kansas State College.

VARIATION OF INDUCTANCE WITH BAR CORE LENGTH, **C. H. Thomas** and **J. C. Burt**, Texas Technological College.

IMPEDANCE RELATIONS OF THREE-WIRE SECONDARY SINGLE PHASE TRANSFORMERS WITH UNBALANCED LOADINGS, **R. W. Townsend**, University of Oklahoma.

CENTRAL PLANT SYSTEM OF AIR CONDITIONING, **Charles Dawson**, Southern Methodist University.

ANALYSIS OF THE INDUCTANCE OF IRON CORE COILS, **R. R. Jenner**, University of Kansas.

TRANSFORMER HEAT RUN BY DIRECT CURRENT OPPOSITION METHOD, **L. W. Gregory**, The Agricultural and Mechanical College of Texas.

MAGNETIC RECORDING, **E. G. Goddard**, New Mexico State College of Agriculture and Mechanic Arts.

A METHOD OF LINE VOLTAGE CONTROL, **A. N. Atsan**, Graduate Student, University of Missouri.

STROBOSCOPIC MEASUREMENT OF SLIP BY BEAT FREQUENCY, **Elmo Crump**, University of Missouri.

At the conclusion of the presentations the judges awarded first place to the paper by C. H. Thomas and J. C. Burt; second place to the paper by R. B. Bonney; and third place to the paper by Elmo Crump.

**Jackson Lectures Published.** "Engineering's Part in the Development of Civilization," a series of six lectures by Dugald C. Jackson (A'87, F'12) has been published as a 114-page cloth-bound volume by The American Society of Mechanical Engineers. These lectures, which were first presented at the University of North Carolina, Raleigh, and printed in the July to December 1938 issues of *Mechanical Engineering*, trace the relation of technological development to human history and stress the responsibility of modern engineering to the future. An article by Dr. Jackson on a related theme "The Social Significance of Engineering," was published in ELECTRICAL ENGINEERING, February 1939, pages 59–63. Copies of the volume of lectures may be secured at $1.55 each from ASME headquarters, 29 West 39th Street, New York, N. Y.

## Future AIEE Meetings

**Summer and Pacific Coast Convention (combined)**
San Francisco, Calif., June 26–30, 1939

**Great Lakes District Meeting**
Minneapolis, Minn., September 27–29, 1939

**Middle Eastern District Meeting**
Scranton, Pa., October 11–13, 1939

**Winter Convention**
New York, N.Y., January 22–26, 1940

# Program Completed for Summer and Pacific Coast Convention

THE AIEE summer and Pacific Coast convention, which will be held in San Francisco, Calif., June 26–30, 1939, by virtue of its location offers members and guests unusual opportunities. As an added attraction the Golden Gate International Exposition on Treasure Island will be in full swing, not to mention the scenic opportunities afforded when traveling to San Francisco from north, east, or south.

Information on the various recreational and social features of the meeting and on scenic attractions for those traveling to and from the convention, together with a tentative schedule of events, appeared in the May issue, pages 217–18. The schedule of events is now complete, with one minor change, as follows: the informal dinner scheduled for 6:00 p.m., Tuesday, June 27, will be held at the Yerba Buena Club instead of in the California State Building. Details of the business and technical program are given in the accompanying tabulation.

## Business and Technical Program

**Advance copies of papers will be made available as approved. Cost: mail orders, 10 cents per copy; if purchased at headquarters or at the meeting, 5 cents per copy. Because preprints are furnished at less than cost, and to avoid bookkeeping expense, payment with order is requested. Coupon books in $1 and $5 denominations are available for those who wish to avoid remittance by check or otherwise.**

### Monday, June 26

8:30 a.m. **Registration (also Sunday, June 25—2:00 to 8:30 p.m.)**

10:00 a.m. **Annual Meeting**

Opening of session. S. J. Lisberger, chairman, summer and Pacific Coast convention committee

Address of welcome. P. M. Downing, past vice-president

Response. Harry W. Hitchcock, nominee for vice-president

Board of directors' report (in abstract) H. H. Henline, national secretary

National treasurer's report. W. I. Slichter

Committee of tellers' report on election of officers

Presentation of president's badge and response from President-Elect F. Malcom Farmer

Presentation of prizes for papers

Presentation of Lamme Medal to Marion A. Savage

President's address. Dr. John C. Parker

2:00 p.m. **Conference of Officers, Delegates, and Members**

### Tuesday, June 27

9:00 a.m. **Power Generation and Transmission**

39-119. MINGLED HYDRO AND STEAM POWER PRODUCTION IN CALIFORNIA—PAST, PRESENT, AND FUTURE. **A. H. Markwart**, Pacific Gas and Electric Company

39-120. THE USE OF MULTI-WINDING TRANSFORMERS WITH SYNCHRONOUS CONDENSERS FOR SYSTEM VOLTAGE REGULATION. **H. P. St. Clair**, American Gas and Electric Service Corporation

39-121. WAVE SHAPE OF 30- AND 60-PHASE RECTIFIER GROUPS. **O. K. Marti**, Allis-Chalmers Manufacturing Company, and **T. A. Taylor**, Bell Telephone Laboratories, Inc.

39-122. LIGHTNING INVESTIGATION ON TRANSMISSION LINES, VII. **W. W. Lewis** and **C. M. Foust**, General Electric Company

9:00 a.m. **Communication, Electronics, and Basic Sciences**

39-146. RECENT DEVELOPMENTS IN TELEGRAPH SWITCHING. **F. E. d'Humy** and **H. L. Browne**, The Western Union Telegraph Company

39-116. IONIZATION TIME OF THYRATRONS. **A. E. Harrison**, California Institute of Technology

39-117. TRANSFORMATION THEORY OF GENERAL STATIC POLYPHASE NETWORKS. **Louis A. Pipes**, Harvard University

39-147. RADIO FREQUENCY HIGH-VOLTAGE PHENOMENA. **A. A. Alford** and **Sidney Pickles**, Mackay Radio and Telegraph Company

9:00 a.m. **Instruments and Measurements and Automatic Stations**

39-124. A HIGH GAIN D-C AMPLIFIER FOR BIO-ELECTRIC RECORDING. **Harold Goldberg**, University of Wisconsin

39-115. SURGE VOLTAGE BREAKDOWN CHARACTERISTICS FOR ELECTRICAL GAPS IN OIL. **R. W. Sorensen**, California Institute of Technology

39-114. THE ANOMALOUS BEHAVIOR OF THE MOVING SYSTEMS OF SINGLE-PHASE A-C WATT-HOUR METERS AT NO LOAD. **F. C. Holtz**, Sangamo Electric Company

39-125. SOME PRACTICAL MEASURING DEVICES. **Lloyd F. Hunt**, Southern California Edison Company

39-93. CARRIER CURRENT LOSSES MEASURED, AND INTERFERENCE MINIMIZED ON BOULDER-LOS ANGELES TRANSMISSION LINES. **J. D. Laughlin**, Bureau of Power and Light, City of Los Angeles, and **W. E. Pakala** and **M. E. Reagan**, Westinghouse Electric and Manufacturing Company

39-126. A NEW TIME STANDARD. **Henry E. Warren**, Warren Telechron Company

# Business and Technical Program

## Wednesday, June 28

**9:00 a.m. General Session**

Address by a nationally known speaker (To be arranged)

**2:00 p.m. Conference of Officers, Delegates, and Members**

**2:00 p.m. Student Technical Sessions**

**7:00 p.m. Student Branch Dinner, Followed by Joint Conference of Student Delegates and Counselors of Eighth and Ninth Districts**

## Thursday, June 29

**9:00 a.m. Protective Devices**

39–132. HIGH-CAPACITY HYDRO-BLAST CIRCUIT BREAKER FOR CENTRAL STATION SERVICE. **W. F. Skeats** and **W. R. Saylor,** General Electric Company

39–128. "MAGNE-BLAST" AIR CIRCUIT BREAKER FOR 5,000-VOLT SERVICE. **E. W. Boehne** and **L. J. Linde,** General Electric Company

39–130. TRANSIENT AND STEADY STATE PERFORMANCE OF POTENTIAL DEVICES. **E. L. Harder, P. O. Langguth,** and **C. A. Woods, Jr.,** Westinghouse Electric and Manufacturing Company

39–127. TWELVE-KV METAL ENCLOSED BUS AND SWITCH STRUCTURE STATION "C," OAKLAND PACIFIC GAS AND ELECTRIC COMPANY. **F. S. Benson,** Pacific Gas and Electric Company, and **H. E. Strang,** General Electric Company

39–129. TESTING OF DISTRIBUTION ARRESTERS. **Herman Halperin,** Commonwealth Edison Company

39–131. SENSITIVE GROUND PROTECTION FOR RADIAL DISTRIBUTION FEEDERS. **Lloyd F. Hunt** and **J. H. Vivian,** Southern California Edison Company, Ltd.

**9:00 a.m. Communication: Joint Session With Institute of Radio Engineers**

IRE paper. THE KLYSTRON AS A GENERATOR OF VERY SHORT WAVES. **W. W. Hansen, R. H. Varian, D. L. Webster,** and **J. R. Woodyard,** Stanford University

39–144. INSTRUMENTS AND METHODS OF MEASURING RADIO NOISE. **C. V. Aggers,** Westinghouse Electric and Manufacturing Company, **Dudley E. Foster,** Radio Corporation of America and **C. S. Young,** Pennsylvania Power and Light Company

39–145. METHODS OF CONTROLLING RADIO INTERFERENCE. **C. V. Aggers,** Westinghouse Electric and Manufacturing Company

IRE paper. THE TECHNICAL FRAMEWORK OF OUR TELEVISION. **E. W. Engstrom,** RCA Manufacturing Company

**9:00 a.m. Electrical Machinery**

39–105. THE HYDROGEN-COOLED TURBINE GENERATOR. **D. S. Snell,** General Electric Company

39–97. HYDROGEN-COOLED TURBINE GENERATORS. **M. D. Ross** and **C. C. Sterrett,** Westinghouse Electric and Manufacturing Company

39–106. SOME FACTORS IN THE MECHANICAL DESIGN OF HIGH-SPEED TURBO-GENERATORS. **S. H. Mortensen,** Allis-Chalmers Manufacturing Company, and **J. J. Ryan,** University of Minnesota

39–107. SPECIAL PROBLEMS OF TWO-POLE TURBINE GENERATORS. **C. M. Laffoon** and **B. A. Rose,** Westinghouse Electric and Manufacturing Company

39–133. THE DIRECT-ACTING GENERATOR VOLTAGE REGULATOR. **W. K. Boice, S. B. Crary, G. Kron,** and **L. W. Thompson,** General Electric Company

39–134. FRACTIONAL-SLOT AND DEAD-COIL WINDINGS. **Michel G. Malti** and **Fritz Herzog,** Cornell University (Presentation by title)

39–135. REPORT OF PROGRESS OF THE ART IN ELECTRICAL MACHINERY. Committee on electrical machinery

**2:00 p.m. Conference on Teaching of Communication and Electronics**

**2:00 p.m. Conference on Sensitive Ground Protection**

This conference is expected to include group discussions of rotating apparatus, high-voltage transmission lines, and distribution circuits, particularly from the relaying point of view. Included in the discussion may be material relating to the flow of current in the earth from grounded conductors as a phenomena

**2:00 p.m. Student Technical Sessions**

## Friday, June 30

**9:00 a.m. Transportation and Lighting**

39–138. SIGNAL SYSTEM, INTERLOCKING PLANTS, AND AUTOMATIC TRAIN CONTROL ON THE SAN FRANCISCO-OAKLAND BAY BRIDGE RAILWAY. **C. R. Davis,** Public Works Department, State of California

39–139. ELECTRICAL EQUIPMENT OF THE UNION PACIFIC STEAM-ELECTRIC LOCOMOTIVE. **M. R. Hanna** and **J. F. Tritle,** General Electric Company

39–137. NEW TYPE OF D-C TO A-C VIBRATOR INVERTER. **O. Kiltie,** General Electric Company

39–136. PAINTING THE GOLDEN GATE INTERNATIONAL EXPOSITION WITH LIGHT. **A. F. Dickerson** and **H. E. Mahan,** General Electric Company

**9:00 a.m. Research and Cables**

39–111. THE DIELECTRIC STRENGTH AND THE LIFE OF IMPREGNATED PAPER—THE INFLUENCE OF THE DENSITY OF THE PAPER. **J. B. Whitehead,** Johns Hopkins University

39–112. DIELECTRIC STRENGTH OF INSULATING LIQUIDS IN A CONTINUOUSLY CIRCULATING SYSTEM. **H. H. Race,** General Electric Company

39–113. TESTS ON OIL IMPREGNATED PAPER, IV—MECHANISM OF BREAKDOWN. **H. H. Race,** General Electric Company

39–140. A NEW TECHNIQUE FOR LEAD CABLE SHEATHING. **B. B. Reinitz** and **R. J. Wiseman,** The Okonite-Callender Cable Company

**9:00 a.m. Industrial Power Applications**

39–141. TEMPERATURE SURVEY OF THE UNITED STATES. **J. J. Smith,** General Electric Company, and **H. W. Tenney,** Westinghouse Electric and Manufacturing Company

39–118. CAPACITOR RELAY TIMING IN INDUSTRIAL CONTROL. **Carroll Stansbury** and **T. B. Jochem,** Cutler-Hammer, Inc.

39–143. ELECTRICAL ENGINEERING AND THE PETROLEUM REFINER. **G. R. Weeks, H. W. Giesecke,** and **C. M. Lathrop,** Standard Oil Development Company

39–142. VARIABLE VOLTAGE EQUIPMENT FOR ROTARY DRILLING RIGS. **E. H. Lamberger,** Westinghouse Electric and Manufacturing Company

# 1939 Lamme Medal Nominations Due December 1

Special attention is directed to the fact that the names of Institute members who are considered eligible for the AIEE Lamme Medal, to be awarded early in 1940, may be submitted by any member in accordance with Section 1 of Article VI of the bylaws of the Lamme Medal committee, as quoted in the following:

> The committee shall cause to be published in one or more issues of ELECTRICAL ENGINEERING, or of its successors, each year, preferably including the June issue, a statement regarding the "Lamme Medal" and an invitation for any member to present to the national secretary of the Institute by December 1, the name of a member as a nominee for the medal, accompanied by a statement of his "meritorious achievement" and the names of at least three engineers of standing who are familiar with the achievement.

Each nomination should give concisely the specific grounds upon which the award is proposed, and also a complete detailed statement of the achievements of the nominee to enable the committee to determine its significance as compared with the achievements of other nominees. If the work of the nominee has been of a somewhat general character in co-operation with others, specific information should be given regarding his individual contributions. Names of endorsers should be given as specified in the foregoing quotation.

The Lamme Medal, founded as a result of a bequest of the late Benjamin Garver Lamme, chief engineer of the Westinghouse Electric and Manufacturing Company (deceased July 8, 1924), provides for the annual award by the Institute of a gold medal—together with bronze replica thereof—to a member of the AIEE "who has shown meritorious achievement in the development of electrical apparatus or machinery"; and for the award of two medals in some years if the accumulation of funds warrants.

The eleventh (1938) Lamme Medal has been awarded to Marion A. Savage (A'21) designing engineer, General Electric Company, Schenectady, N. Y., "for able and original work in the development and improvement of mechanical construction and the efficiency of large high-speed turbine alternators." Presentation will be made during the AIEE summer convention at San Francisco, Calif., June 26–30, 1939. A biographical sketch of Mr. Savage appeared in the March issue, page 136.

**ASA Lists Codes and Standards.** The American Standards Association, joint agency of which the AIEE is a member-body, recently issued its annual indexed list of American standards and safety codes. The list includes about 400 nationally approved codes, standards, and specifications indexed alphabetically and also industrially by subject. Civil, mechanical, and electrical engineering, transportation, ferrous and nonferrous metallurgy, chemical industry, mining, petroleum, wood, pulp and paper, textiles, symbols and abbreviations are among the fields covered. More than 600 trade, technical, and governmental groups took part in developing these standards. Copies of the list may be obtained without charge from ASA headquarters, 29 West 39th Street, New York, N. Y.

# Coolidge Receives Faraday Medal of the IEE at Springfield Meeting of North Eastern District

PRESENTATION of the Faraday Medal of The Institution of Electrical Engineers, Great Britain, to W. D. Coolidge (A'10, M'34) Director of the General Electric Company's Research Laboratory, Schenectady, N. Y., was a feature of the recent Springfield meeting of the Institute's North Eastern District. Dr. Coolidge is the third American to receive the Faraday Medal, previous recipients having been Elihu Thomson and Frank B. Jewett. Presentation of the medal and certificate to Dr. Coolidge was made by AIEE Past-President Gano Dunn who officiated in his capacity as Local Honorary Secretary of the IEE for the United States. The award to Dr. Coolidge was previously announced in ELECTRICAL ENGINEERING (March 1939, page 137), and the full text of Dr. Dunn's presentation address and of Dr. Coolidge's response may be found elsewhere in this issue.

Co-featured on the general session program Thursday morning, May 4, preceding the Faraday medal ceremony, were President John C. Parker of the AIEE and President C. W. Kellogg of the Edison Electric Institute. Selecting "socialization" as his topic, President Parker carefully defined the difference between "socialization" and "collectivization," pointing out that engineering in the broad sense is a pretty well socialized activity "by virtue of the way it penetrates and affects all walks of life." Dr. Parker urged each engineer to take his full place in civic affairs "so that folks will better know the engineer and the engineer better know the general public." Speaking on the topic "The Engineer as a Citizen," Mr. Kellogg further developed the same basic thought and presented some compelling facts and figures reflecting the current situation in the United States. These addresses are scheduled for publication in full text in an early issue of ELECTRICAL ENGINEERING. Present for the opening of the general session was Mayor R. L. Putnam of Springfield. Vice-President C. L. Dawes presided.

Traditions of the North Eastern District were upheld by the committee responsible for the Springfield meeting, in the program facilities for student participation, and in the industrial flavor of the general technical program. Something of a novelty in District meeting programs was what might be called the preview presentation of five papers scheduled for the forthcoming summer convention in San Francisco. The total registration figure of 439 is analyzed in the accompanying tabulation. Session attendance ranged from 65 to about 100, and averaged about 55; average for the two parallel student sessions was 95.

Supplementing the technical program, facilities for inspection trips to industries included the Bigelow Sanford Carpet Company, Thompsonville, Conn.; Stevens Paper Company, Westfield, Mass.; Chapman Valve Manufacturing Co., Indian Orchard, Mass.; Package Machinery Company, Springfield, Mass.; United States Armory, Springfield, Mass.; Westinghouse Electric and Manufacturing Co., East Springfield; Fisk Rubber Company, Chicopee, Mass.; Pratt and Whitney Aircraft Corp., Hartford, Conn. Some of these trips, especially that to the carpet plant, were enjoyed by women as well as men. Two highlights of the women's entertainment program were dinner and bridge at the Springfield Country Club Wednesday evening, and a "college cruise" Thursday that included visits to Mount Holyoke College, The Notch, Amherst, Massachusetts State College, Calvin Coolidge Memorial Bridge, Smith College; luncheon was served at Wiggins Old Tavern, Northampton. Climax of the entertainment program was the banquet held at the Hotel Kimball, Thursday evening, May 4, with Past Vice-President W. H. Timbie serving as toastmaster. Responding to invitation, President Parker and National Secretary Henline spoke briefly. President Parker called on the older Institute leaders to remember their own youth and "give way for the young men," and called on the younger men to take an increasingly active part in Institute affairs. Secretary Henline endorsed President Parker's idea and gave some brief citations of recent Institute activities—such as Houston meeting of the South West District, the Washington, D. C., Section student program, and New York Section joint student meeting—as an indication of the way this idea is being carried out.

Prize awards made at the banquet by Vice-President C. L. Dawes covering the preceding year were as follows: Best paper prize, C. W. LaPierre and A. P. Mansfield for their paper "Photoelectric Weft-Straightener Control," presented at the North Eastern District meeting, Lenox, Mass., in May 1938; best branch paper, divided between E. G. Schroeder of Rensselaer Polytechnic Institute for his paper "Investigation of Heat Dissipation and Temperature Rises in Underground Ducts," and P. P. Koliss and Joseph Ezen of Worcester Polytechnic Institute for their paper "Analysis of an Electron Tube-Controlled Induction Motor"; both papers presented at Lenox in May 1938.

At the Springfield meeting, left to right: North Eastern District Secretary R. G. Lorraine, National Secretary H. H. Henline, Vice-President C. L. Dawes, Springfield Section Chairman W. O. Henschke, President J. C. Parker, and Editor G. R. Henninger

Featured address of the evening was delivered by Dr. John L. Davis, professional lecturer and prominent minister of a New York Methodist Church. After amusing his audience for some time with a running fire of witty comments, speaking on the subject "dimensions of life" he gave further emphasis to the theme enunciated earlier in the evening by Doctor Parker, listing the early ages at which a host of prominent scientists made some of their most important discoveries and technical contributions. The banquet was attended by 114 persons.

### STUDENT TECHNICAL SESSIONS

Honors for technical session attendance went to the two parallel student sessions, with approximately 200 between them. To provide an outlet for the greatest possible number of student papers, the District committee on student activities under the chairmanship of Professor E. M. Strong of Cornell University arranged for the parallel sessions, one designated as a communication and measurement session and the other as a power session. As noted in the following listings, some 15 papers by 21 authors were presented:

**Communication and Measurements Session—C. A. Lister,** Tufts College, Chairman

An Instrument for the Measurement of Microvolts at Supersonic Frequencies, **M. A. Schultz,** Massachusetts Institute of Technology.

A Substitute for the Radio Range in Instrument Flight Training, **R. B. Roe,** Cornell University.

The Solution of Amplifier Circuits by Operational Methods, **R. B. Rittenburg,** Tufts College.

Frequency-Selective Feedback for Improvement of Acoustical Response of an Audio-Frequency Sound System, **W. N. Brown, Jr.,** and **E. W. Sheridan,** Massachusetts Institute of Technology.

Stroboscopic Device for Sound-Wave Demonstration, **W. K. Halstead** and **W. G. Tuller,** Massachusetts Institute of Technology.

A Kinetic Power-Time Graph Demonstrator, **E. L. Foster,** Cornell University.

The "Glo-Relay," a New Method of Initiating Vapor Discharges, **E. C. Dench,** Worcester Polytechnic Institute.

**Power Session—A. H. Sullivan, Jr.,** Cornell University, Chairman

Experimental Flux Plotting, **W. C. Phillips, Jr.,** Tufts College.

A Thyratron Controlled Automatic Speed Governor, **H. T. O'Neill** and **J. F. Clancy,** Northeastern University.

A Study of Automobile Engine Ignition, **R. F. Gilkeson,** Cornell University.

Study of a Self-Excited A-C Generator, **F. L. Miller** and **W. W. West,** Brown University.

Breakdown Strength of Dielectrics in Presence of X-Rays, **L. F. Kilham, Jr.,** Tufts College.

A Calorimetric Method for Determining Losses in Electrical Machines, **H. S. Blauvelt, G. V. Pearson,** and **C. W. Thulin,** Worcester Polytechnic Institute.

A Smoke Eliminator, **Phil Smith,** University of New Hampshire.

A Thyratron Method of Lighting Control for Small Theaters, C. R. Wischmeyer, Yale University.

Each of the two groups of papers were judged separately for participation in the District's program of student prize awards. From the communication and measurements group, the judges awarded first prize for effective presentation to W. N. Brown, Jr., and E. W. Sheridan; second prize to E. C. Dench. Of the power session group, first prize for presentation was awarded to L. F. Kilham, Jr.; second prize to H. T. O'Neill and J. F. Clancy. Subsequent review and examination of the student technical papers will provide the basis for the final District awards which probably will be announced at the 1939 District student conclave.

## CONFERENCE ON STUDENT ACTIVITIES

For the consideration of problems incidental to the conduct of student activities in the North Eastern District, a luncheon conference was held at the Highland Hotel, Springfield, Friday, May 5. Last year this group had, after considerable discussion, decided in favor of two parallel sessions for the presentation of student technical papers. Inasmuch as the two sessions at Springfield were held after this conference, there was no opportunity for discussing the results of the practical application of that decision. However, the notable success of the Springfield student program subsequently spoke for itself. An exchange of comments pertaining to 1940, when the annual summer convention of the Institute will be held at Swampscott with the consequent elimination of the District meeting for that year, led to the tentative decision to hold a joint student conference probably May 3, 1940. Several schools have offered to act as host for such a conference, but no decision was made. Conversation points toward Worcester Polytechnic Institute.

All 16 of the student branches in the North Eastern District were represented, by a total of 33 faculty or enrolled student members of which the following constituted the official delegates:

**Student Branch Counselors and Alternates**

C. W. Henderson, Syracuse University, Syracuse, N. Y.

Victor Siegfried, Worcester Polytechnic Institute, Worcester, Mass.

L. C. Holmes, Rensselaer Polytechnic Institute, Troy, N. Y.

A. G. Conrad, Yale University, New Haven, Conn.

R. O. Buchanan, University of Vermont, Burlington, Vt.

F. N. Tompkins, Brown University, Providence, R. I.

J. D. Cobine, Harvard University, Cambridge, Mass.

G. S. Brown, Massachusetts Institute of Technology, Cambridge, Mass.

E. A. Walker, Tufts College, Tufts College, Mass.

R. G. Porter, Northeastern University, Boston, Mass.

E. M. Strong, Cornell University, Ithaca, N. Y.

G. J. Fiedler, Union College, Schenectady, N. Y.

W. B. Hall, Rhode Island State College, Kingston.

L. W. Hitchcock, University of New Hampshire, Durham, N. H.

A. S. Hill, University of Maine, Orono, Maine.

### Analysis of Registration at Springfield

| Classification | Springfield Section | District 1* | Other Districts | Totals |
|---|---|---|---|---|
| | Location | | | |
| Members | 34 | 157 | 37 | 228 |
| Students | 0 | 153 | 3 | 156 |
| Men Guests | 8 | 20 | 4 | 32 |
| Women Guests | 10 | 11 | 2 | 23 |
| Totals | 52 | 341 | 46 | 439 |

* Outside Springfield.

**Student Branch Chairman and Alternates**

J. Leo Raesler, Syracuse University, Syracuse, N. Y.

H. L. Anderson, Worcester Polytechnic Institute, Worcester, Mass.

L. D. Runkle, Rensselaer Polytechnic Institute, Troy, N. Y.

J. G. Stephenson, Yale University, New Haven, Conn.

E. C. Bailey, University of Vermont, Burlington, Vt.

W. W. West, Brown University, Providence, R. I.

R. M. Hutchinson, Harvard University, Cambridge, Mass.

R. B. Lawrence, Massachusetts Institute of Technology, Cambridge.

M. L. Greenough, Tufts College, Tufts College, Mass.

Crawford Adams, Cornell University, Ithaca, N. Y.

D. P. Campbell, Union College, Schenectady, N. Y.

H. G. Crook, Rhode Island State College, Kingston.

Phil Smith, University of New Hampshire, Durham, N. H.

H. M. Kenney, University of Maine, Orono, Maine.

M. J. Mulhern, Clarkson College of Technology, Potsdam, N. Y.

Others among the total of 39 persons attending the conference included Past-Presidents Charles F. Scott and D. C. Jackson, National Secretary H. H. Henline, Vice-President C. L. Dawes, Chairman E. M. Strong of the District committee on student activities, District Secretary R. G. Lorraine, Editor G. R. Henninger, Burton Hall of Rhode Island State College, and E. R. McKee of the University of Vermont.

## DISTRICT EXECUTIVE COMMITTEE MEETING

A luncheon-business session of the District executive committee was held Wednesday, May 3. Chairman Strong of the District committee on student activities reported briefly for his special committee that has been studying the matter of a new and more satisfactory basis for the rating of student technical papers. The committee long has contended that methods of rating applicable to formal technical program papers are neither satisfactory nor equitable for the grading of student technical papers, which are intended to accomplish a fundamentally different purpose. Tentatively, Professor Strong's committee recommended that for student papers, 10 points be allowed for introduction; 50 points for speaking technique, including personal characteristics and manner of delivery; 50 points for style, including the speaker's organization of material; 10 points for summary and conclusion; 20 points for manner and effectiveness in handling discussion. Pursuant to favorable action by the executive committee, Professor Strong's committee is to report in detail to Chairman R. W. Sorensen of the AIEE Committee on Student Branches, in the hope that the subject will be discussed at the annual conference of officers, delegates and members to be held in conjunction with the summer convention in San Francisco next month. Another problem to be submitted for summer convention discussion is the matter of the District student prizes particularly with respect to papers prepared by graduate students, where so few papers are available in the ordinary year that effective competition or equitable competitive rating is a difficult matter. Provisions were made for an augmented District co-ordinating committee to meet May 13 at the New Ocean House, Swampscott, Mass., with officers of the Boston and Lynn Sections and hotel authorities for the purpose of perfecting preliminary plans for the 1940 summer convention scheduled to be held at Swampscott. (This meeting was held as scheduled.)

Official attendants at the meeting included the following:

C. L. Dawes, vice-president, AIEE
R. G. Lorraine, secretary, North Eastern District
E. M. Strong, chairman, North Eastern District committee on student activities
W. O. Henschke, chairman, Springfield Section
W. W. Cotner, chairman, Ithaca Section
F. A. Faron, chairman, Connecticut Section
C. W. LaPierre, representing Schenectady Section
J. G. Patterson, chairman, Boston Section
C. E. Tuites, secretary, Rochester Section
L. Wetherill, chairman, Pittsfield Section

Others in attendance included Past Vice-President A. C. Stevens of Schenectady, Director K. B. McEachron of Pittsfield, Student Counselor Victor Siegfried of Worcester Polytechnic Institute, Past Chairman F. N. Tompkins of the District committee on student activities, National Secretary H. H. Henline and Editor G. R. Henninger of New York.

A group of student authors and others who participated in the student sessions at the Springfield meeting

## Future Meetings of Other Societies

**American Association for the Advancement of Science.** June 19–24, Milwaukee, Wis.

**American Institute of Mining and Metallurgical Engineers.** 151st general meeting, July 10–13, San Francisco, Calif.

**American Physical Society.** 228th meeting, June 23–24, Princeton, N. J.

229th meeting, June 28–30, Stanford University, Calif.

**American Society for Testing Materials.** 42d annual meeting, June 26–30, Atlantic City, N. J.

**American Society of Civil Engineers.** Annual convention, July 26–29, San Francisco, Calif.

**American Society of Heating and Ventilating Engineers.** Semiannual meeting, July 4–6, Mackinac Island, Mich.

**American Society of Mechanical Engineers.** Semiannual meeting, July 10–15, San Francisco, Calif.

Fall meeting, September 4–8, New York, N. Y.

**Illuminating Engineering Society.** 33d annual convention, August 21–25, San Francisco, Calif.

**Institute of Radio Engineers.** National convention, June 27–30, San Francisco, Calif.

Fortieth annual convention, September 20–23, New York, N. Y.

**International Conference on High-Voltage Systems (CIGRE).** Tenth meeting, June 29–July 8, Paris, France.

**Society for the Promotion of Engineering Education.** 47th annual meeting, June 19–23, The Pennslyvania State College, State College, Pa.

**Industrial Research Institute Election.** Election of new officers and members of its executive committee has been announced by the Industrial Research Institute, as follows: *Chairman*—H. W. Graham, Jones and Laughlin Steel Corporation, Pittsburgh, Pa.; *Vice-Chairman*—H. E. Hoover, The Hoover Company, Chicago, Ill.; *Members*—L. W. Wallace, The Crane Company, Chicago, Ill.; F. W. Blair, Proctor and Gamble Company, Ivorydale, Ohio. The committee is composed of executives in charge of research laboratories. The Industrial Research Institute was formed in 1938 to provide research men in industry with an organization in which they could exchange information on laboratory organization, administration, and other problems. (*EE, Oct. '38, p. 429*)

**ASCE to Hold International Meeting.** The Institution of Civil Engineers of Great Britain and the Engineering Institute of Canada will be guests of the American Society of Civil Engineers at its Fall meeting, to be held in New York, N. Y., September 1939, in connection with the New York World's Fair. A comprehensive program of technical meetings, social events, inspections, and sight-seeing has been arranged for the meeting, which will open September 4. The technical and some of the social aspects of the program will center around Columbia University, while its supplementary features will be in connection with the World's Fair.

# Section and Branch Activities

## Annual Report for 1938–39

THE following constitutes the annual report on Institute Section and Branch activities for the fiscal year which ended April 30, 1939. Similar information for three preceding fiscal years appeared in ELECTRICAL ENGINEERING for June 1938, pages 263–6; June 1937, pages 762–5; June 1936, pages 752–4.

Present members of the Sections committee and the committee on Student Branches, which supervise the two important divisions of Institute activities covered by this report, are: Sections—H. H. Race, *chairman*, M. S. Coover, W. M. Dann, O. W. Holden, E. T. Mahood, I. Melville Stein, W. H. Timbie, and, *ex-officio*, the chairmen of all Sections of the Institute; Student Branches—R. W. Sorensen, *chairman*, R. H. Dearborn, E. E. Dreese, W. C. DuVall, G. A. Irland, F. Ellis Johnson, C. W. Ricker, Charles F. Scott, E. M. Strong, and, *ex-officio*, all Student Branch counselors.

### Table I. Section Meetings Held During Year Ending April 30, 1939

| Section | AIEE Members August 1937 | AIEE Members August 1938 | Meetings During Year Number | Meetings During Year Average Attendance | Average Attendance as Per Cent of Membership, August 1938 |
|---|---|---|---|---|---|
| Akron | 63 | 76 | 8 | 63 | 83 |
| Alabama | 48 | 39 | 4 | 56 | 144 |
| Baltimore | 188 | 201 | 11 | 163 | 81 |
| Boston | 409 | 411 | 8 | 215 | 52 |
| Central Indiana | 135 | 123 | 7 | 147 | 119 |
| Chicago | 674 | 697 | 6 | 291 | 42 |
| Power group | | | 5 | 105 | |
| Industrial group | | | 3 | 59 | |
| Cincinnati | 175 | 182 | 10 | 218 | 120 |
| Study discussion group | | | 7 | | |
| Cleveland | 285 | 300 | 9 | 190 | 63 |
| Technical group | | | 5 | 66 | |
| Mansfield Division* | | | 3 | | |
| Columbus | 79 | 87 | 5 | 214 | 246 |
| Connecticut | 266 | 267 | 9 | 143 | 54 |
| Dallas | 101 | 114 | 9 | 132 | 116 |
| Denver | 160 | 168 | 8 | 85 | 51 |
| East Tennessee | 76 | 102 | 9 | 46 | 45 |
| Erie | 63 | 67 | 9 | 58 | 87 |
| Florida | 66 | 68 | 1 | 128 | 188 |
| Fort Wayne | 86 | 88 | 8 | 116 | 132 |
| Georgia | 83 | 97 | 8 | 185 | 191 |
| Houston | 89 | 116 | 11 | 174 | 150 |
| Iowa | 53 | 50 | 7 | 62 | 124 |
| Ithaca | 54 | 47 | 8 | 70 | 149 |
| Kansas City | 122 | 124 | 9 | 115 | 93 |
| Lehigh Valley | 197 | 193 | 9 | 96 | 50 |
| Los Angeles | 470 | 486 | 8 | 139 | 29 |
| Louisville | 49 | 50 | 8 | 86 | 172 |
| Lynn | 128 | 130 | 11 | 477 | 366 |
| Technical lectures | | | 5 | 450 | |
| Madison | 64 | 64 | 5 | 174 | 272 |
| Mansfield* | | | 1 | 136 | |
| Memphis | 53 | 53 | 11 | 56 | 106 |
| Mexico | 67 | 66 | 4 | 74 | 112 |
| Michigan | 353 | 342 | 9 | 150 | 44 |
| Round table discussions | | | 5 | 27 | |
| Milwaukee | 268 | 297 | 7 | 318 | 107 |
| Minnesota | 88 | 83 | 8 | 120 | 145 |
| Power committee | | | 1 | 55 | |
| Montana | 39 | 39 | 3 | 94 | 241 |
| Muscle Shoals | 33 | 40 | 13 | 44 | 110 |
| Nebraska | 55 | 58 | 8 | 71 | 122 |
| New Orleans | 64 | 78 | 8 | 89 | 114 |
| New York | 3,308 | 3,346 | 5 | 375 | 11 |
| Power group | | | 11 | 267 | |
| Communication group | | | 8 | 350 | |
| Transportation group | | | 3 | 133 | |
| Basic science group | | | 2 | 138 | |
| Illumination group | | | 3 | 308 | |
| Niagara Frontier | 218 | 205 | 7 | 290 | 141 |
| North Carolina | 77 | 78 | 1 | 148 | 190 |
| Oklahoma City | 97 | 106 | 11 | 202 | 191 |
| Philadelphia | 571 | 580 | 8 | 212 | 37 |
| Pittsburgh | 464 | 503 | 8 | 188 | 37 |
| Pittsfield | 150 | 167 | 8 | | |
| Technical meetings | | | 6 | | |
| Colloquium meetings | | | 4 | | |
| Portland | 119 | 125 | 11 | 192 | 154 |
| Transmission and distribution committee | | | 8 | 47 | |
| Communication committee | | | 1 | 55 | |
| Providence | 93 | 95 | 7 | 54 | 57 |
| Rochester | 92 | 94 | 11 | 115 | 122 |
| Communication group | | | 3 | 33 | |
| Power group | | | 2 | 16 | |
| St. Louis | 240 | 247 | 10 | 82 | 33 |
| San Antonio | 35 | 37 | 8 | 45 | 122 |
| San Diego† | | | 4 | 36 | |
| San Francisco | 442 | 457 | 10 | 144 | 32 |
| Technical meetings | | | 6 | 70 | |
| Saskatchewan | 25 | 25 | 8 | 47 | 188 |
| Schenectady | 397 | 428 | 13 | 247 | 58 |
| Technical discussion meetings | | | 4 | | |
| Seattle | 144 | 156 | 10 | 125 | 80 |
| Power group | | | 1 | 35 | |
| Electronics group | | | 1 | 68 | |
| Sharon | 77 | 80 | 9 | 126 | 157 |
| Spokane | 55 | 62 | 8 | 148 | 238 |
| Springfield | 68 | 57 | 9 | 69 | 121 |
| Syracuse | 73 | 73 | 3 | 220 | 301 |
| Toledo | 78 | 78 | 8 | 62 | 79 |
| Toronto | 309 | 348 | 13 | 150 | 42 |
| Discussion group | | | 2 | 124 | |
| Tulsa | 61 | 88 | 8 | 146 | 166 |
| Urbana | 58 | 65 | 9 | 144 | 221 |
| Utah | 59 | 56 | 9 | 113 | 202 |
| Vancouver | 99 | 98 | 11 | 62 | 63 |
| Virginia | 92 | 92 | 1 | 80 | 87 |
| Washington | 256 | 288 | 10 | 155 | 54 |
| Technical sessions | | | 2 | 80 | |
| Wichita | 27 | 33 | 10 | 46 | 139 |
| Worcester | 67 | 69 | 9 | 158 | 229 |
| Total....67 | 13,054 | 13,539 | | | |

Total number of meetings.............. 635
Total attendance......................85,692

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* Mansfield division of Cleveland Section became Mansfield Section March 6, 1939.
† Organized January 18, 1939.

### Table II. Section Meetings Held During Last Three Fiscal Years

| | Fiscal Year Ending April 30 | | |
|---|---|---|---|
| | 1937 | 1938 | 1939 |
| Number of Sections | 62 | 65 | 67 |
| Number of meetings held | 621 | 624 | 635 |
| Average number of meetings | 10.0 | 9.6 | 9.5 |
| Total attendance | 74,950 | 110,148 | 85,692 |
| Average attendance per meeting | 121 | 177 | 135 |

## SECTION ACTIVITIES

Two new Sections were organized during the year, San Diego in January, and Mansfield in March, bringing the total number to 67. A Mansfield division of the Cleveland Section had previously been organized, and had held three meetings while securing a sufficient number of new members to meet the requirement for a Section.

All of the Sections were active during the past year. The total number of meetings reported to headquarters was 635, the largest number ever reported, which indicates that the increase in activity noted in the two fiscal years immediately preceding has been maintained.

President Parker visited many Sections, and his addresses were enthusiastically received.

The name of the Detroit-Ann Arbor Section was changed to Michigan Section with no change in territory. The San Francisco Section Territory was expanded to include six counties in western Nevada.

### Table III. Prizes Awarded by Sections

| Section | Number of Papers Presented | Amounts of Awards |
|---|---|---|
| Houston | 2 | $10, $5 |
| Iowa | 8 | $25 and Standard Handbook |
| Los Angeles | 6 | $15.00 |
| Lynn | 8 | $15, $10, $5 |
| | 8 | $15, $10, $5 |
| Minnesota | 4 | $15, $10, $5, $5 |
| New Orleans | 2 | Attendance prize |
| New York | 6 | $25, $10 |
| Oklahoma City | | $15, $10, $5 |
| Pittsfield* | 6 | $15, $10 |
| Portland | 4 | $10 |
| St. Louis | 5 | $15, $10, $5 |
| San Francisco | 3 | $10 |
| Schenectady* | 6 | $25 (divided) |
| Toronto | 4 | Two prizes |
| Tulsa | | Three prizes |
| Utah | 4 | $10 |

* Two meetings in competition between Sections.

The group and special meeting plans inaugurated in previous years by many Sections were continued with excellent success, and a few new groups were organized. The meetings of these groups are reported in table I.

The Cleveland Section organized a technical group which held five meetings. The Philadelphia Section organized a communication group, and also inaugurated a weekly luncheon club. The name of the electrophysics group of the New York Section was changed to basic science group.

### Table IV. Branch Meetings Held During Year Ending April 30, 1939

| | Meetings During Year | | |
|---|---|---|---|
| Branch | Number | Average Attendance | Approximate Number of Talks by Students |
| Akron, University of | 9 | 27 | 5 |
| Alabama Polytechnic Institute | 7 | 34 | 2 |
| Alabama, University of | 13 | 17 | 9 |
| Arizona, University of | 16 | 9 | 10 |
| Arkansas, University of | 16 | 40 | 11 |
| Armour Institute of Technology | 12 | 44 | |
| British Columbia, University of | 18 | 23 | 21 |
| Brooklyn, Polytechnic Institute of | | | |
| Day Division | 9 | 61 | 1 |
| Evening Division | 4 | 34 | 4 |
| Brown University | 9 | 45 | |
| Bucknell University | 14 | 27 | 4 |
| California Institute of Technology | 22 | 38 | 4 |
| California, University of | 26 | 48 | 3 |
| Carnegie Institute of Technology | 26† | 49 | 22 |
| Case School of Applied Science | 18† | 62 | 23 |
| Catholic University of America | 5 | 14 | 2 |
| Cincinnati, University of | 4 | 61 | 6 |
| Clarkson College of Technology | 7 | 30 | |
| Clemson Agricultural College | 7 | 27 | 10 |
| Colorado State Agricultural College | 7 | 15 | 3 |
| Colorado, University of | 12 | 56 | 3 |
| Columbia University | 7 | 27 | 2 |
| Cooper Union | | | |
| Day Division | 7 | 23 | 2 |
| Evening Division | 9 | 20 | 6 |
| Cornell University | 5 | 36 | 4 |
| Denver, University of | 8 | 40 | |
| Detroit, University of | 5 | 41 | |
| Drexel Institute | 16 | 30 | 3 |
| Duke University | 12 | 20 | 9 |
| Florida, University of | 12 | 28 | 1 |
| George Washington University | 8 | 34 | 3 |
| Georgia School of Technology | 6 | 76 | |
| Harvard University | 5 | 72 | |
| Idaho, University of | 9 | 47 | 1 |
| Illinois, University of | 6 | 85 | 2 |
| Iowa State College | 11 | 83 | |
| Iowa, University of | 16 | 36 | 17 |
| Johns Hopkins University | 12 | 23 | 10 |
| Kansas State College | 13† | 97 | 19 |
| Kansas, University of | 9 | 41 | 5 |
| Kentucky, University of | 19 | 125 | 3 |
| Lafayette College | 6 | 16 | 4 |
| Lehigh University | 3 | 68 | 1 |
| Lewis Institute | 8 | 32 | |
| Louisiana State University | 5 | 24 | 4 |
| Louisville, University of | 10 | 18 | 8 |
| Maine, University of | 9 | 15 | 4 |
| Marquette University | 7 | 54 | 4 |
| Maryland, University of | 8 | 26 | 7 |
| Massachusetts Inst. of Technology | 14 | 53 | 5 |
| Michigan Col. of Mining & Technology | 3 | 43 | 1 |
| Michigan State College | 15 | 28 | |
| Michigan, University of | 8 | 95 | |
| Milwaukee School of Engineering | 7 | 53 | 7 |
| Minnesota, University of | 6 | 82 | |
| Mississippi State College | 5 | 46 | 1 |
| Missouri School of Mines & Metallurgy | 9 | 43 | 4 |
| Missouri, University of | 9 | 34 | 4 |
| Montana State College | 27† | 30 | 84 |
| Nebraska, University of | 16 | 45 | 12 |
| Nevada, University of | 10 | 41 | 2 |
| Newark College of Engineering | 2 | 48 | |
| New Hampshire, University of | 11 | 33 | 3 |
| New Mexico State College* | 7 | 18 | 6 |
| New Mexico, University of | 7 | 20 | 5 |
| New York, College of the City of | | | |
| Day Division | 10 | 48 | |
| Evening Division | | | |
| New York University | | | |
| Day Division | 4 | 32 | 1 |
| Evening Division | | | |
| North Carolina State College | 13 | 41 | 13 |
| North Dakota State College | 6 | 12 | 4 |
| North Dakota, University of | 13 | 12 | 7 |
| Northeastern University | 15 | 56 | 3 |
| Northwestern University | 7 | 30 | |
| Notre Dame, University of | 8 | 39 | 3 |
| Ohio Northern University | 7 | 30 | 3 |
| Ohio State University | 11 | 51 | 6 |
| Ohio University | 2 | 18 | |
| Oklahoma A. & M. College | 10 | 143 | 7 |
| Oklahoma, University of | 10 | 54 | 6 |
| Oregon State College | 9 | 62 | 7 |
| Pennsylvania State College | 5 | 106 | |
| Pennsylvania, University of | 8 | 24 | 7 |
| Pittsburgh, University of | 14† | 96 | 8 |
| Porto Rico, University of | 7 | 36 | |
| Pratt Institute | 14 | 43 | 4 |
| Princeton University | 5 | 15 | 5 |
| Purdue University | 17 | 250 | |
| Rensselaer Polytechnic Institute | 4 | 95 | |
| Rhode Island State College | 10 | 33 | 2 |
| Rice Institute | 1 | 6 | 2 |
| Rose Polytechnic Institute | 4 | 25 | 6 |
| Rutgers University | 3 | 29 | |
| Santa Clara, University of | 10 | 25 | 8 |
| South Carolina, University of | 12 | 26 | |
| South Dakota State College | 10 | 18 | 3 |
| South Dakota State School of Mines | 13 | 35 | |
| Southern California, University of | 16 | 18 | 6 |
| Southern Methodist University | 8 | 36 | 3 |
| Stanford University | 10 | 30 | 4 |
| Stevens Institute of Technology | | | |
| Swarthmore College | 8 | 11 | |
| Syracuse University | 19 | 36 | 13 |
| Tennessee, University of | 5 | 39 | |
| Texas A. & M. College | 12 | 44 | 7 |
| Texas Technological College | 14 | 17 | 6 |
| Texas, University of | 9 | 69 | 1 |
| Tufts College | 8 | 30 | 5 |
| Tulane University | 9 | 27 | 8 |
| Union College | 4 | 51 | |
| Utah, University of | 11 | 32 | 4 |
| Vermont, University of | 11 | 24 | 3 |
| Villanova College | 6 | 11 | 2 |
| Virginia Military Institute | 10† | 42 | 13 |
| Virginia Polytechnic Institute | 18 | 75 | 13 |
| Virginia, University of | 3 | 25 | 2 |
| Washington, State College of | 14 | 47 | 6 |
| Washington, University of | 11 | 88 | 11 |
| Washington University | 8 | 42 | 2 |
| West Virginia University | 17 | 37 | 112 |
| Wisconsin, University of | 3 | 41 | |
| Worcester Polytechnic Institute | 9 | 87 | 2 |
| Wyoming, University of | 9 | 13 | 1 |
| Yale University | 8 | 18 | |
| Total....120 | | | 725 |

Total number of meetings.............. 1,190
Total attendance......................53,380

* Authorized by Executive Committee, December 16, 1938.

† Attendance at all or nearly all meetings required by faculty, as indicated in questionnaire distributed by chairman of committee on Student Branches.

### Table V. Branch Meetings Held During Last Three Fiscal Years

| | Fiscal Year Ending April 30 | | |
|---|---|---|---|
| | 1937 | 1938 | 1939 |
| Number of Branches | 119 | 120 | 120 |
| Number of meetings held | 1,363 | 1,334 | 1,190 |
| Average number of meetings | 11.5 | 11.1 | 9.9 |
| Total attendance | 46,121 | 60,446 | 53,380 |
| Average attendance per meeting | 33.8 | 45.3 | 44.8 |
| Number of student talks | 1,130 | 897 | 725 |

The Michigan Section held a series of round-table discussions.

The Portland Section held classes in symmetrical components. The power group of the New York Section offered courses in structural planning and design, electrical engineering review, engineering economics and practice, law for engineers, public speaking, television, and diathermy and X rays.

The Pittsfield and Schenectady Sections held their tenth annual competition in two joint meetings, one in each city, with three speakers representing each Section at each meeting. Prizes of $15 and $10 were awarded at each meeting.

Brief information regarding prizes offered by a considerable number of Sections is given in table III.

The Toronto Section continued its practice of holding meetings of the discussion group and the technical discussion group immediately preceding a large majority of the regular Section meetings.

The Cincinnati Section continued with good success its meetings of the study-discussion group for consideration of articles in ELECTRICAL ENGINEERING dealing with professional development and engineering education.

The executive committee of the New York Section requested that the members of the Section indicate on a return post card their reactions to a proposed amendment to the state education law tending to make mandatory six years of scholastic training for licensing as a professional engineer. Eighty-eight per cent of the approximately 1,700 Section members who had voted by May 15 were opposed to the proposed amendment.

The committee on safety wrote the Sections suggesting that each have presented a paper dealing with accident prevention or remedial measures after electrical shock. The replies indicated that in general the Sections were making arrangements to carry out the suggestion.

Tables I, II, and III contain detailed information on Section activities. Table VI gives a comprehensive record of co-operation between Sections and Branches.

## BRANCH ACTIVITIES

A new Branch organized at the New Mexico State College restored the total number to 120, after the University of North Carolina Branch was discontinued due to a consolidation of the engineering school with that at North Carolina State College.

The total number of Branch meetings was materially below the number reported for each of the two preceding fiscal years. Only one Branch failed to report any activity. Eighteen Branches held more than 15 meetings each, 61 held from 8 to 15, 32 held from 4 to 7, and 9 held fewer than 4 meetings.

President Parker visited a considerable number of Branches, some separately, and in a few cases he spoke at joint meetings attended by representatives of several Branches. He also attended the dinner meeting held in connection with the conference on student activities of the Middle Eastern District, in Washington, D. C.

### Table VI. Section or Joint Section and Branch Meetings With Active Student Participation

| Sections | Schools | Date | Student Talks | Attendance |
|---|---|---|---|---|
| Los Angeles | California Institute of Technology<br>University of Southern California | 5/10/38 | 6 | 105 |
| Cincinnati | University of Cincinnati | 5/12/38 | 3 | 65 |
| New Orleans | Louisiana State University | 5/13/38 | 3 | 79 |
| Oklahoma City and Tulsa | University of Arkansas<br>Oklahoma A. & M. College<br>University of Oklahoma | 5/13/38 | 3 | 110 |
| Portland | Oregon State College | 5/14/38 | 4 | 90 |
| St. Louis | Missouri School of Mines & Met.<br>University of Missouri<br>Washington University | 5/20/38 | 5 | 88 |
| Utah | University of Utah | 5/23/38 | 5 | 35 |
| Nebraska | University of Nebraska | 10/19/38 | | 153 |
| Portland | Oregon State College | 11/15/38 | | 93 |
| San Antonio | University of Texas | 12/5/38 | 1 | 83 |
| Toronto | University of Toronto | 12/9/38 | 4 | 70 |
| New Orleans | Tulane University | 1/20/39 | 2 | 75 |
| Dallas | Southern Methodist University | 1/31/39 | | 122 |
| Nebraska | University of Nebraska | 2/9/39 | | 80 |
| Vancouver | University of British Columbia | 3/6/39 | 4 | 37 |
| Kansas City | University of Kansas | 3/16/39 | 1 | 64 |
| Houston | Rice Institute<br>Texas A. & M. College | 3/22/39 | 2 | 76 |
| Minnesota | University of Minnesota | 4/18/39 | 4 | 55 |
| Iowa | Iowa State College<br>University of Iowa | 4/20/39 | 8 | 82 |
| Central Indiana | Purdue University | 4/21/39 | | 175 |
| Spokane | University of Idaho<br>Washington State College | 4/27/39 | 1 | 67 |
| San Francisco | University of California<br>University of Santa Clara<br>Stanford University | 4/21/39 | 3 | 100 |
| Totals—20 Sections, 30 Branches | | | 59 | 1,904 |

### Table VII. Conferences on Student Activities

| District or Section | Location | Date |
|---|---|---|
| 7 | Kansas State College, Manhattan | 5/7/38 |
| 1 | Lenox, Mass. (North Eastern District meeting) | 5/20/38 |
| 8 and 9, University of British Columbia | Portland, Ore. (Pacific Coast convention) | 8/9/38 |
| 2 | Washington, D. C. | 11/4–5/38 |
| 4 | Miami, Fla. (Southern District meeting) | 11/28/38 |
| Pittsburgh Section | Pittsburgh, Pa. | 1/10/39 |
| 7 | Houston, Tex. (South West District meeting) | 3/19/39 |
| 6 | Laramie, Wyo. | 3/21–22/39 |

On a questionnaire sent to the Branches by the committee on Student Branches, all except 6 of 62 replies indicated voluntary attendance and participation in the activities.

Although a large majority of the Branches had some papers presented by students, the total number of such papers was far below the number in each of the two preceding fiscal years. This important phase of Branch activity should receive increased attention.

### Table VIII. Student Conventions

| Sponsor (District, Section, or Branch) | Location | Date | Number of Student Papers |
|---|---|---|---|
| 7 | Kansas State College, Manhattan | 5/6–7/38 | 22 |
| 1 | Lenox, Mass. (North Eastern District meeting) | 5/19–20/38 | 6 |
| 8 and 9, University of British Columbia | Portland, Ore. (Pacific Coast convention) | 8/10–11/38 | 10 |
| 4 | Miami, Fla. (Southern District meeting) | 11/28/38 | 6 |
| Pittsburgh Section | Pittsburgh, Pa. | 1/10/39 | 4 |
| 7 | Houston, Tex. (South West District meeting) | 4/18–19/39 | 14 |
| 6 | University of Wyoming, Laramie | 4/21–22/39 | 9 |
| 3 and New York Section | Cooper Union, New York, N. Y. | 4/27/39 | 6 |
| Purdue University Branch | Lafayette, Ind. | 4/29/39 | 2 |

Of 1,564 enrolled students whose terms, according to Institute records, were expected to expire on April 30, 1939, 849 or about 54 per cent applied for admission as Associates. Some of the students were eligible to continue enrollment because they had remained in school. For the preceding fiscal year, the corresponding figures were 1,474, 703, and about 48 per cent.

Students have continued their active participation in the Pacific Coast convention and District meeting programs. Student sessions were held as follows: North Eastern District meeting, Lenox, Mass., May 18–20, 1938, 1 session, 6 papers; Pacific Coast convention, Portland, Ore., August 9–12, 1938, 2 sessions, 10 papers; Southern District meeting, Miami, Florida, November 28–30, 1938, 1 session, 6 papers; South West District meeting, Houston, Texas, April 17–19, 1939, 3 sessions, 14 papers.

The committee on safety, with the approval of the committee on Student Branches, wrote the counselors of the Student Branches suggesting that each Branch have presented a paper dealing with the prevention of accidents or remedial measures after electrical shock. The replies indicated much interest in carrying out the suggestion.

Tables IV and V contain information on Branch meetings, table VI gives a record of co-operation between Sections and Branches, and tables VII and VIII present summarized data on student conferences and conventions.

## AIEE National Prize Awards Announced for 1938 Papers

After consideration of all eligible papers, the AIEE committee on award of Institute prizes has announced the national prize awards for papers presented during 1938. The award for best paper in public relations and education is the first since 1936, and in accordance with the provisions of the present rules, the committee considered all papers under this classification presented since that year. The prizes will be presented during the Institute’s combined summer and Pacific Coast convention, San Francisco, Calif., June 26–30. The committee consists of H. S. Osborne, *chairman*, J. W. Barker, E. C. Crittenden, and I. Melville Stein.

Papers and their authors receiving awards in the various classifications are as follows:

### BEST PAPERS

*Best Paper in Engineering Practice.* This prize was awarded to C. F. Wagner (A’20, M’27) for his paper “Unsymmetrical Short Circuits on Water-Wheel Generators Under Capacitive Loading,” published in ELECTRICAL ENGINEERING (AIEE TRANSACTIONS) for November 1937, pages 1385–95, and presented at the winter convention, New York, N. Y., January 24–28, 1938.

Honorable mention was made of the following papers: “A Carrier Telephone System for Toll Cables,” by C. W. Green (A’1 , M’26) and E. I. Green (A’23, M’30) presented at the winter convention, New York, N. Y., January 24–28, 1938, and published in the 1938 TRANSACTIONS (May section) pages 227–36; “The PCC Street Car,” by C. F. Hirshfeld (A’05, F’36, deceased) presented at the winter convention, New York, N. Y., January 24–28, 1938, and published in the 1938 TRANSACTIONS (February section) pages 61–66.

*Best Paper in Theory and Research.* This prize was awarded to K. S. Wyatt (A’32), D. L. Smart (A’37), and J. M. Reynar, for their paper “Mechanical Uniformity of Paper-Insulated Cables,” published in the 1938 TRANSACTIONS (March section) pages 141–54, and presented at the winter convention, New York, N. Y., January 24–28, 1938.

Honorable mention was made of the paper “Amplitudes of the Magnetomotive Force Harmonics for Fractional Slot Windings,” by J. F. Calvert (A’27, M’35) presented at the summer convention, Washington, D. C., June 20–24, 1938, and published in the 1938 TRANSACTIONS, pages 777–84.

*Best Paper in Public Relations and Education.* This prize was awarded to R. W. Sorensen (A’07, F’19) for his paper “The Economic Status of the Engineer,” published in the 1938 TRANSACTIONS, pages 786–9, and also in ELECTRICAL ENGINEERING, July 1938, pages 281–85, and presented at the summer convention, Washington, D. C., June 20–24, 1938.

### INITIAL PAPER

Prize for initial paper was awarded to S. J. Rosch (A’15) for his paper “The Current-Carrying Capacity of Rubber Insulated Cables,” published in the 1938 TRANSACTIONS (March section) pages 155–67, and presented at the winter convention, New York, N. Y., January 24–28, 1938.

Honorable mention was made of the following papers: “Noise Co-ordination of Rural Power and Telephone Systems,” by H. W. Wahlquist (M’36) and T. A. Taylor (A’30, M’36) published in the 1938 TRANSACTIONS (November section) pages 613–20, and presented at the winter convention, New York, N. Y., January 24–28, 1938; “A Symbolic Analysis of Relay and Switching Circuits,” by Claude E. Shannon, published in the 1938 TRANSACTIONS, pages 713–23, and presented at the summer convention, Washington, D. C., June 20–24, 1938.

### BRANCH PAPER

Prize for Branch paper was awarded to John L. C. Lof for his paper “A Method for Determining the Efficiencies of Small Motors From the Heat Due to Eddy Currents.”

Honorable mention was made of the paper “An Investigation of Some of the Properties of a Non-Linear Circuit,” by R. W. Warburton and W. W. Murdoch.

Awards being made by the various AIEE Districts for 1938 papers will be announced in future issues, as this information becomes available.

**Physics Meeting in Switzerland.** Members of AIEE are invited to attend an International Meeting on Physics which will be held in Zurich, Switzerland, September 4–16, 1939, in connection with the Swiss National Exhibition. The meeting, which is sponsored by the Federal Institute of Technology of Switzerland, and the Physical Society of Zurich, will include a two-day program on television, the same time as the second international television meeting.

# Current Items From American Engineering Council

## Questionnaire on Patents for Engineers and Inventors

As announced in the February 1939 issue (page 88) American Engineering Council has undertaken a factual inquiry into the American patent system in co-operation with the National Association of Manufacturers and the National Industrial Conference Board. It is considered of primary importance in this inquiry to ascertain whether patents have had their intended usefulness to the engineer as an inventor. Has he been able successfully to put to use his inventions and derive a satisfactory benefit from them? Does the patent provide him with a positive and effective means to assert his claims against others who have devised similar technical improvements? What channels have been made available to him through the patent to convey title to his invention to those who can make best use of it, and what obstacles has he encountered?

To obtain a broad and representative cross section of the experience of engineers at large, a questionnaire has been prepared by F. E. Raymond, director of the joint patent inquiry. Some of the more significant questions included are:

1. How have you put your patents to use?
2. What are the principal reasons for the non-use of your patents?
3. Have you encountered any premeditated opposition from others to the working or use of your patents?
4. How many of your patents have been involved in litigation?
5. Have any of your patent applications been denied?
6. What rewards or satisfactions (other than monetary) have come to you through your patented inventions?

All AIEE members who have had any experience with the patent system are urged to request a copy of this questionnaire from American Engineering Council, 744 Jackson Place, Washington, D. C., fill in the answers to the various questions, and return it promptly to Council headquarters in order that the joint patent inquiry may have available the broadest possible cross section of experiences of electrical engineers. All replies will be treated strictly confidentially.

## Federal Public Works Agencies Combined by Presidential Order

Exercising the authority granted him under the new reorganization act, President Roosevelt on April 25 submitted to Congress the first of three plans for re-grouping the functions of various agencies of the Federal Government, to become effective in 60 days unless disapproved, as a whole, by a majority vote of both the Senate and the House of Representatives within that period, or unless Congress in the meantime adjourns. Since the House on May 3 voted down a resolution of disapproval, only an early adjournment could prevent its taking effect on June 24. To the Federal Works Agency proposed by the President will be transferred the functions and personnel of “those agencies of the Federal Government dealing with public works not incidental to the normal work of other departments, and which administer federal grants or loans to state and local governments, or other agencies, for the purpose of construction.”

Transferred to the Federal Works Agency will be the Bureau of Public Roads, now in the Department of Agriculture; the Public Buildings Branch of the Procurement Division, Treasury Department (which designs and supervises construction of federal buildings in all parts of the country); the Branch of Building Management of the National Parks Service, Department of Interior, which selects sites for and determines the order of construction of public buildings in the District of Columbia; the United States Housing Authority, now in the Department of the Interior (slum-clearance); the Public Works Administration; and the Works Progress Administration (both independent agencies set up on a temporary basis). Still unchanged is the present supervision of the Corps of Engineers over river and harbor improvements and flood control works, since this agency was specifically exempted by the reorganization act.

Heading the new agency will be a Federal Works Administrator, to be appointed by the President with the advice and consent of the Senate, at a salary of $12,000 per year, and an Assistant Federal Works Administrator at $9,000. In general, the present heads of the units transferred to the agency will be retained and will report to the Administrator. Any personnel in excess of the needs of the new agency will be transferred to other government posts or given a preferred status on eligible lists for future employment.

The general plan for reorganization, as set forth in the President's message, envisions two additional new agencies to be known as the Federal Security Agency and the Federal Loan Agency. The present major independent agencies of the government (except those exempted by law) will be attached either to one of these three, to one of the ten existing executive departments, or, in a few instances, to the White House executive office.

# Standards

## The Place of the IEC in Electrical Standardization

In an effort to acquaint the Institute membership more fully with the standards activities of the Institute, the AIEE standards committee, through its newly appointed subcommittee on publicity, has initiated a series of articles for publication in ELECTRICAL ENGINEERING. The first, published in the April issue, discussed the interrelations between the Standards activities of the AIEE and of the American Standards Association. In the May issue, the appointment of four co-ordinating committees of the standards committee was announced, and one of these four committees announced its objectives and tentative plans of action. In the following item, the work of the International Electrotechnical Commission and its relationship to the Standards activities of the Institute are discussed. It was prepared by J. W. McNair (A'25) secretary, United States National Committee of the IEC, and electrical engineer, American Standards Association.

The International Electrotechnical Commission (IEC) was founded in 1906 as a result of the resolution passed by the chamber of government delegates at the International Electrical Congress in St. Louis, Mo., in 1904. Its object is to provide permanent machinery whereby any international problem of standardization in the electrical field may be given continuous and effective study. It is composed of 26 national committees which are representative of all sections of electrical industry in their respective countries. The IEC undertakes problems of electrical standardization when requested to do so by the electrical industry of any country speaking through the medium of its national committee.

The IEC is an example of the benefit of giving continuous study to difficult problems as against the intermittent study formerly given by infrequent international conferences, especially when the problems are complicated by constantly changing factors and by the economic conditions in the different nations. Much of the work of the IEC is devoted to the preparation of internationally acceptable recommendations used to facilitate international trade in electrical machinery and apparatus. These recommendations enable purchasers to compare on a uniform basis offers to supply apparatus regardless of from what country the bids are received.

Much work has been done also on questions of systems of electrical units and the naming of units and magnitudes, standardization of letter and graphical symbols in the electrical field, and the preparation of an international electrotechnical vocabulary.

The recommendations of the IEC represent an international consensus of opinion and are accepted by the national committees for international purposes. The national committees when accepting these recommendations are under no obligation to adopt these rules as their own national standards. It is understood, however, that they will use their best efforts to harmonize their national requirements with IEC recommendations in so far as conditions permit.

The work of the IEC is carried forward by 27 permanent advisory committees (see table). These committees are under the administrative direction of a particular national committee, known as the secretariat, which accepts this responsibility. The subjects cover various types of electrical machinery and apparatus, insulating oils and insulating materials, measuring instruments, etc., and also include steam, hydraulic, and internal-combustion prime movers. The work has resulted to date in the approval of 24 IEC recommendations. Some of these have been revised several times in the effort to keep them up to date. In addition, there is a series of dimensional specifications for lamp bases and sockets and gauges therefor. Most of the IEC publications and reports may be obtained from the American Standards Association, 29 West 39th Street, New York, N. Y.

Plenary meetings of the IEC are held every three years in the different countries. At these meetings all of the advisory committees meet which have active work before them. In the intervals between plenary meetings, groups of five or six advisory committees having extremely active work before them meet twice each year. In 1939 such meetings will be held in New York in September and in Zurich, Switzerland, in October, the last plenary meeting of the IEC having been held in Torquay, England, in June 1938.

The meetings in New York will be held September 5 to 8 and will cover the following subjects: transformers, hydraulic turbines, switchgear, internal-combustion engines, electric welding, insulation co-ordination. The meetings in Zurich will be held October 2 to 5 and will cover the following subjects: graphical symbols, aluminium, electric-traction equipment, radio communication, measuring instruments, electronic devices.

The administrative affairs of the Commission are conducted by an executive group, known as the committee of action, which ordinarily meets once a year although it is empowered to meet twice a year if necessary. Between plenary meetings the committee of action is empowered to authorize the publication of IEC recommendations which have been submitted to, and voted favorably upon by, the national committees under a six-months rule. The Commission maintains a central office in London to manage its affairs. This office is under the direction of Charles le Maistre (A'12) who has been general secretary of the IEC since its organization.

### THE UNITED STATES NATIONAL COMMITTEE

The United States National Committee (USNC) was formed by the AIEE in 1906 and was represented that year at the organization meeting of the IEC in London. The AIEE continued to sponsor the USNC and defray its expenses, except for the con-

### International Electrical Projects Under IEC Procedure

1. Nomenclature, U. S. National Committee
2. Rating of electrical machinery, British National Committee
3. Symbols, Swiss National Committee
4. Hydraulic turbines, U. S. National Committee
5. Steam turbines, U. S. National Committee

6. Lamp caps and holders, Central Office
7. Aluminum, Central Office
8. Voltages and high-voltage insulators, Italian National Committee
9. Electric-traction equipment, French National Committee
10. Insulating oils, Central Office

11. Rules and regulations for overhead lines, Belgian National Committee
12. Radio communications, Dutch National Committee
13. Measuring instruments, German National Committee
14. Rating of rivers, U. S. National Committee
15. Shellac, British National Committee

16. Terminal markings, Dutch National Committee
17. Oil switches and circuit breakers, Swedish National Committee
19. Internal-combustion engines, U. S. National Committee
20. Electric cables, British National Committee
21. Accumulators, German National Committee

22. Electronic devices (for power applications)
23. Electrical fittings
24. Electrical and magnetic magnitudes and units
25. Letter symbols
26. Electric welding
27. Electro-heating

tributions of money and services by individuals and companies, until 1920, when the desirability of broadening the base for the work became evident. Accordingly, an invitation was extended to, and accepted by, the American Society for Testing Materials (ASTM), the American Society of Mechanical Engineers (ASME), the National Electric Light Association (NELA), and the National Electrical Manufacturers Association (NEMA) to participate in the work. Under these auspices the USNC functioned until 1932 when, on the initiative of the AIEE, an agreement was made with the American Standards Association (ASA) whereby the work was integrated with the broader field of the ASA, and the ASA assumed the administrative expenses of the USNC.

A considerable simplification of the technical organizations responsible for the work of the USNC took place as a result of the consolidation of the USNC work with that of the ASA. The USNC was originally a committee organized solely for IEC purposes, and the ASA had for many years an electrical advisory committee for its purposes. With the reorganization, this electrical advisory committee was reorganized and renamed the electrical standards committee. The membership of this committee consists of 18 representatives of 12 member organizations. The AIEE, the NEMA, and the ASA electric light and power group have three representatives each, and the following organizations have one representative each: American Society for Testing Materials, American Transit Association, Association of American Railroads, ASA communication group, ASA fire protection group, Institute of Radio Engineers, United States Department of Commerce—National Bureau of Standards, United States Navy Department, and United States War Department. The USNC was then set up to be composed of the members of the electrical standards committee, plus three representatives from the American Society of Mechanical Engineers and a group of members-at-large distinguished for their contributions to international standardization work and electrical engineering in general. The chairman of the electrical standards committee since its inception, and in fact since the organization of the old electrical advisory committee, is C. R. Harte (A'10, M'32) of the Connecticut Company, New Haven. Sidney Withington (M'20, F'24) of the New York, New Haven and Hartford Railroad Company is vice-chairman. The president of the USNC is C. H. Sharp (A'02, F'12) who has served in that capacity continuously since the consolidation in 1932 and for many years previous to that time. Other officers are: A. E. Kennelly (A'88, F'13, HM'33) *honorary president;* and C. R. Harte (A'10, M'32) and H. S. Osborne (A'10, F'21) *vice-presidents.* AIEE representatives on the USNC are: V. M. Montsinger (A'14, F'29), H. S. Osborne, and R. E. Hellmund (A'05, F'13); alternates: H. E. Farrer (A'21), E. L. Moreland (A'11, F'21), and E. B. Paxton (A'22, M'25).

The USNC handles the technical work of the 27 IEC projects by assigning the primary responsibility for each to an individual known as technical advisor. The technical advisor secures the broad opinion of American industry through an advisory committee. Prior to the consolidation, the USNC had specially organized groups of advisors for this purpose. Since the consolidation, the sectional committees of the ASA have served as the advisory committees wherever there existed such committees covering the work in question. Regular ASA committees now take care of the work in all but four cases. In the last few years the work of the IEC has been increasing so fast that if some consolidation had not been made much difficulty and confusion inevitably would have resulted. Under the procedure of the ASA, sectional committees are so organized as to contain representation of all branches of the electrical industry having a real interest in the work. In addition, the membership of the committees must be so arranged that neither the producers nor consumers have a majority of the members.

In all this work, the AIEE is continuing to play the vital part which it has since the inception of the work of the IEC. The Institute has an ideal setup for conducting the underlying discussions and research work necessary for the development of new standards and for revising old standards to bring them in line with the ever-changing conditions of present-day industry. The material thus developed, when fed into the regularly organized machinery of the ASA and, where desirable, on to the IEC, constitutes the basis for American Standards and the American point of view on international standards.

# Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or reject them entirely.

ALL letters submitted for consideration should be the original typewritten copy, double spaced. Any illustrations submitted should be in duplicate, one copy to be an inked drawing but without lettering, and the other to be lettered. Captions should be furnished for all illustrations.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

## Electricity for Treasure Island

*To the Editor:*

I note that in the article entitled "Electricity for Treasure Island" in the April issue of ELECTRICAL ENGINEERING, contrast is drawn in several places on pages 150 and 151, between "fluorescent" lamps and "Mazda" lamps. This is an unfortunate error; the term "Mazda" is applied by the manufacturers to both fluorescent and incandescent lamps.

Very truly yours,

W. S. H. HAMILTON (A'19, M'26)

(Chairman, AIEE Committee on Transportation; Equipment Electrical Engineer, New York Central System, New York, N. Y.)

## The Student Engineer and "Electrical Engineering"

*To the Editor:*

I wish to amplify the importance and utility of the student engineer and his place in the engineering journal as brought to light so nobly by Doctor Sorensen (*EE, April '39, p. 181–82*). If we were to glance over the other national engineering society publications, we would readily feel that we were acting in a negative direction as far as student activities are concerned. If we were to retrocess the past several months we would find numerous data in ELECTRICAL ENGINEERING which has for its main theme "the student engineer." The student in these articles was inoculated with much ingenious material of a valuable future nature. This material was given much care and detailed thought as pointed out in the symposium dealing with "Co-ordination of Physics With Electrical Engineering," "Graduate Training for Engineers," "Training Engineering Graduates in Industry," and many others. All the articles were either written by engineers in industry, or by engineering educators, aimed directly at the student. The student then becomes similar to the defendant before the judge in which he has little or nothing to say. We could offer remedially in the case of the student the "Sorensen Method" or the student page. As matters stand at present we do not have a perfect equilibrium because the student does not have any medium in which to express his viewpoints, the viewpoints being along the lines of student training, graduate courses, engineering and mathematics, and many others.

In relation to student graduate courses most men feel that after they have put in four years of time, energy, and money in an engineering course, they are desirous to go in the field and apply their potential abilities. The average student after four years in college finds his interest at a minimum and has no desire to continue his course immediately. My observation has been that some students have in mind at the time of graduation the intent of going back to school, either night or day, after one or two years in industry. At the time of graduation a very small percentage of the students have any definite specialization in mind. Those that have some definite thing in mind do not continue due to the lack of money, or because they feel that the school does not have ample facilities, to take care of their desires. Men in my class felt that specialization could be obtained more efficiently in industry.

In the co-ordination of mathematics and

physics with engineering, most students felt that their knowledge of mathematics although they covered a two year period was insufficient to analyze and derive a large percentage of problems. This was especially true when the calculus had to be used whereby it acted as a medium in solving problems. The general attitude of calculus as a tool in solving problems seems universal in most colleges in that the student dodges it as much as he possibly can. The reason in my opinion that a student and even practicing engineers avoid calculus as much as possible is due to their poor understanding of the subject. Most men in my class felt that insufficient time was devoted to physics, and that physics that involved an understanding of the higher mathematics was taught before the mathematics was taught. We all agreed, including the instructor, that if more time was spent on the fundamentals of physics less time in the future would have to be spent on electrical engineering.

These are a few of the reactions of a class of electrical engineers to some of the phases of the art and science. If the student page were made part of the engineering journal much more detail could be analyzed by individual students, which would prove advantageous to instructor, industry, and student alike.

Yours very truly,
HERBERT JAY COBBS (A'39)

(Jamaica, N. Y.)

## Engineering Education

*To the Editor:*

Of course every engineer is loyal to his *Alma Mater*—the best college in the world, with the best faculty, the best professors and teachers, the best alumni, and the best students. *Rah! Rah! Rah!* Now that we have that out of our systems suppose we, who are accustomed to deal with facts, prepare a little questionnaire to be submitted to the faculties of all the colleges except the one we honored by permitting it to engrave our names on some of its sheepskins:

1*a*. What proportion of your teaching force was receiving a salary of $5,000 or over from some industrial organization, when you invited them to assist in preparing your young men to become engineers?

1*b*. $2,500 to $5,000?

2. What proportion of your 1938 graduates were more healthy than when they entered college, because of habits of exercise, study, rest, and diet you trained them to follow?

3*a*. What proportion of your 1938 graduates were placed by your efforts in positions in keeping with the technical course you gave them?

3*b*. What was the average starting wage?

4. Do you train ALL your graduates by forums, debates, etc., to know how to talk intelligently and convincingly on matters of concern to all citizens of the United States? (This would give them ability to express their ideas on engineering matters as well.)

There probably was a time when our colleges, to meet expenses, had to accept almost any boy left by devoted, self-sacrificing parents at the college gate. Now, however, the number of applicants has so increased that the colleges in self-defense can select by rigid examination those whose qualifications make them the most promising. The colleges cannot be blamed for the raw material turned over to them for polishing; rather they are to be commended for the results they do achieve with many unpromising specimens.

In economics the law of supply and demand is often referred to, but in educational institutions the supply of students appears unlimited and the demand for graduates often seems nonexistent. As in the case of wheat and cotton, pork and beef, the trouble is underconsumption, and we must as a people learn to utilize more intelligently the thousands of young men who have received an engineering education.

When these young engineers emerge with their sheepskins, they are of such an age that their chief aim in life is to have a home of their own. It would seem hardly more than fair that after four years of preparation, they should be assured a modest salary which would enable them to be normal, useful, self-supporting citizens. After working faithfully for four years and completing a course of training prescribed by those who are paid to know how to prepare men for an engineering career, it is stark tragedy for a graduate to learn that his diploma is chiefly an expensive ornament. The college which accepts tuition, should guarantee a technical job of some kind at not less than $30 a week to each graduate or so modify its courses of training that it will be able to do so.

Until colleges perfect their four year courses of training for the engineering profession, it is obviously futile to consider postgraduate work for, with properly arranged four-year courses, postgraduate work should be unnecessary.

Colleges should be developing not merely technicians, but useful citizens whose trained habits of thought and reasoning should enable them to lead the nation in its crusade "to establish justice, insure domestic tranquility, and promote the general welfare of all the people of the United States."

Very truly yours,
WM. B. TAYLOR (A'05, M'16)

(Plympton, Mass.)

## A Modified Slip Test for Measuring Synchronous Reactance

*To the Editor:*

It has been my experience that the slip test originally proposed by Haga[1] for determining the direct and quadrature synchronous reactances[2] of salient-pole machines quite frequently gives unsatisfactory results when performed in the usually prescribed way for power laboratory experiments. Several disturbing factors are those introduced by hunting due to slip-pulsation of magnetic reluctance; tendency of the generator under test to pull into step and run as a synchronous machine; and errors introduced in reading extreme deflections of ammeter (and voltmeter) needle when correct conditions are finally obtained.

In power laboratories where the equipment is available, a slightly different test can be made which would seem to be more reliable and certainly more instructive to students interpreting the data for the first time. The set used in our laboratories was a three-machine set consisting of a d-c motor coupled directly to two 15-kva salient-six-pole a-c generators, one of which has a rotatable stator resulting from its electrodynamometer construction. With machines wye-connected, the output of the fixed-stator machine was fed to the movable-stator unit and field adjustment made for approximately rated current of 40 amperes. Obviously this arrangement gives complete synchronism between the rotating field on the stator and the field structure of the machine under test. By rotating the stator through some 180 electrical degrees, the entire periodic variation of synchronous reactance could be observed from the readings of ammeter and voltmeter, while for any fixed position of the stator, readings were entirely steady.

The results showed a quadrature-axis reactance of 2.3 ohms per wye phase, and a direct-axis reactance of 3.6 ohms, the latter value being identical with the usual synchronous reactance determined from short-circuit data and the air-gap line for the magnetic circuit of the machine.

It might be mentioned that this test could also be performed with a two-machine set if the driving unit were a synchronous motor. However, in this case some means might have to be available for controlling the alternating voltage impressed on the generator under test.

REFERENCES

1. Haga, Lumière Électrique, 7, Series 2, 329, 1909.

2. THE REACTANCES OF SYNCHRONOUS MACHINES, R. H. Park and B. L. Robertson. AIEE TRANSACTIONS, volume 47, 1928, pages 514–35.

Yours very truly,
HENRY B. HANSTEIN (A'26)

(Instructor in electrical engineering, College of the City of New York, N. Y.)

## Tensors and Electrical Networks

*To the Editor:*

As I noted in a letter published in the January 1938 issue of ELECTRICAL ENGINEERING, a widespread misconception has been created as to what tensors will do in the theory of electrical networks. As pointed out, Professor Struik, in a set lecture before the American Mathematical Society, said that tensor analysis as used by Kron enabled one to transform one network into another. The quotation to the same effect in the present discussion is from Kron's new book on tensors ("Tensor Analysis of Networks," Gabriel Kron, John Wiley and Sons, Inc., New York, 1939). Professor Synge, who has addressed the AIEE (1935 Summer convention, Ithaca, N. Y.) and the American Mathematical Society (last St. Louis meeting) on tensors and the application of tensor analysis to electrical-network theory, has written me to the effect that he has understood that this type of transformation was possible. Statements to the same effect have been made publicly before the Society for the Promotion of Engineering Education.

In the analysis which follows I examine this claim critically and find it to be almost baseless. For the sake of clarity, I have taken the simplest possible network but the argument can be generalized to networks of any complexity.

In vector analysis, a tensor means a linear vector operator or dyadic giving a collineation or affine transformation. In tensor analysis the tensor is defined more broadly by a law of transformation with respect to the totality of co-ordinate systems of the linear group. The older viewpoint of vector analysis was implicit in my original note "On the Impedance as a Tensor" (*Philosophical Magazine,* June 1924, page 1094), in the later papers of Kron and Sah on dyadics, and in the fundamental monographs by Cauer, Quade, and Burington on matrices. The newer viewpoint is desirable in certain branches of geometry, certain geometrical interpretations of dynamics, and is necessary in the theory of relativity, but in the theory of electrical networks it is not necessary nor, as will be proved, generally applicable.

Let $I_1, I_2, \ldots$ be the currents in the branches of an electric network, say the network having the delta connection represented in figure 1, and consider the transformation

$$\left.\begin{aligned} I_1 &= I_1' + I_2' + I_3' \\ I_2 &= \qquad\; I_2' + I_3' \\ I_3 &= \qquad\qquad\;\; I_3' \end{aligned}\right\} \qquad (1)$$

selected at random. As all admissable co-ordinate systems are on a parity in the tensor viewpoint, the primed currents must be branch currents: implying figure 2. But

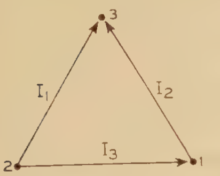


**Figure 1**

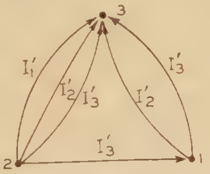


**Figure 2**

by Kirchhoff's condition at the junctions, as ordinarily understood, the nullity of figure 2 is different from that of figure 1. Hence figure 2 is ruled out and the primed variables cannot have the same physical interpretation as the unprimed. Only the latter are true branch currents and the former are merely linear combinations of them having no proper graphical nor physical interpretation. Hence the graph of the new variables, if there is one, must be figure 3.

But the admissibility of figure 3 is not secure. Consider the Kirchhoff constraints $NI = 0$ for figure 1, where

$$N = \begin{vmatrix} 0 & 1 & -1 \\ 1 & 0 & 1 \\ -1 & -1 & 0 \end{vmatrix} \qquad I = \begin{vmatrix} I_1 \\ I_2 \\ I_3 \end{vmatrix}$$

Under the transformation (1) they become $NAI' = 0$ where

$$A = \begin{vmatrix} 1 & 1 & 1 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{vmatrix} \qquad NA = \begin{vmatrix} 0 & 1 & 0 \\ 1 & 1 & 2 \\ -1 & -1 & -2 \end{vmatrix}$$

From the tensor principle of parity of co-ordinate systems $NA$ implies figure 4 in the same way that $N$ implies figure 1. But figure 4 is in disagreement with figure 3 and the two figures are reconcilable only when $I_1 = I_2 = I_3 = 0$.

We may describe this situation by saying that the branch currents form an absolute reference system. The only admissible transformation of them in the tensor sense is the identity.

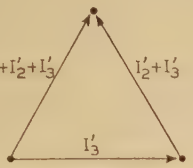


**Figure 3**

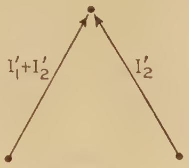


**Figure 4**

There is also evidence that the junction points form an absolute reference system in a similar way from the fact that most transformations on them lead to meaningless corresponding graphs; for example, the derived incidence matrix given by Professor Tucker in ELECTRICAL ENGINEERING, May 1937, page 620, has no graphical or physical interpretation.

It has been claimed recently that "it is possible to establish a non-singular transformation matrix between any two $n$-coil networks, no matter how many meshes, junction pairs, and sub-networks each one has." As this result is in conflict with the findings here given if the transformation is on the branch currents, and in conflict with dynamics if on the loop currents, a critical examination of this much-heralded result of the tensor viewpoint becomes necessary.

Consider the problem of finding the transformation which will carry the series connection of figure 5 over into the parallel connection of figure 6. Our procedure may be as follows:

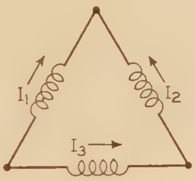


**Figure 5**

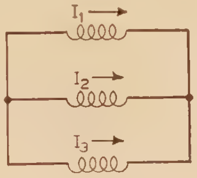


**Figure 6**

First, introduce the loop-currents proper $i_1', i_1'', i_2''$.

Second, extend the graphs to figures 7, 8, respectively.

Third, introduce the loop currents $i_2', i_3', i_3''$ as required by the nullity of the new figures.

Fourth, write down the relation between the branch currents and the loop currents for the respective cases:

$$\begin{vmatrix} I_1 \\ I_2 \\ I_3 \end{vmatrix} = \begin{vmatrix} 1 & 1 & 0 \\ -1 & 0 & 0 \\ -1 & 0 & 1 \end{vmatrix} \begin{vmatrix} i_1 \\ i_2 \\ i_3 \end{vmatrix},$$

$$\begin{vmatrix} I_1 \\ I_2 \\ I_3 \end{vmatrix} = \begin{vmatrix} 1 & 0 & 1 \\ -1 & 1 & 0 \\ 0 & -1 & 0 \end{vmatrix} \begin{vmatrix} i_1 \\ i_2 \\ i_3 \end{vmatrix}$$

These equations may be written

$$I' = C_1 i' \quad I'' = C_2 i''$$

where the primes and double primes distinguish the columnar matrices in the two cases.

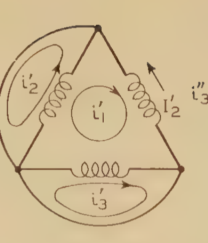


**Figure 7**

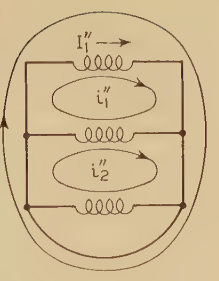


**Figure 8**

Since $C_1$, $C_2$ represent, in an obvious way, the *graphs* of figures 7 and 8, respectively, and since we can write

$$C_2 = (C_2 C_1^{-1}) C_1 \qquad (2)$$

$$C_2 = C_1 (C_1^{-1} C_2) \qquad (3)$$

we have

graph 2 = operation on graph 1

The operators in cases (2) and (3) are, respectively

$$C_a = \begin{vmatrix} 0 & -2 & 1 \\ 1 & 2 & 0 \\ -1 & -1 & 0 \end{vmatrix} \qquad C_b = \begin{vmatrix} 1 & -1 & 0 \\ 0 & 1 & 1 \\ 1 & -2 & 0 \end{vmatrix}$$

We next remark that the matrix equation

$I'' = C_a I'$ is a consequence of writing $i' = i''$
$i' = C_b i''$ is a consequence of writing $I' = I''$

so that $C_b$, as the matrix of the transformation on the generalized currents, carries the network of the impedance matrix $Z$ over into $\bar{Z} = C_b^T Z C_b$, where

$$Z = \begin{vmatrix} z_1 + z_2 + z_3 & z_1 & -z_3 \\ z_1 & z_1 & 0 \\ -z_3 & 0 & z_3 \end{vmatrix},$$

$$\bar{Z} = \begin{vmatrix} z_1 + z_2 & -z_2 & z_1 \\ -z_2 & z_2 + z_3 & 0 \\ z_1 & 0 & z_1 \end{vmatrix}$$

The following points may now be made:

1. No external electromotive forces will encounter the same impedance in the new network that it did in the old.
2. The network of figure 5 has not been carried over to that of figure 6 since the equations $i_2' = i_3' = i_3'' = 0$ do not hold.
3. All impedance branches are *permanently short-circuited!*

This $C_b$, which applies only to networks with short-circuited impedance branches and gives only networks with short-circuited impedance branches, is Kron's $C'$ ("Tensor Analysis of Networks," pages 418–33, page 152, etc.). The presence of externally impressed currents and electromotive forces and complexity in the network do not alter the true situation but may, of course, conceal it.

Tensor analysis has legitimate though academic application in a determination of network properties invariant with respect to the choice of sets of independent loop currents, but when this analysis has once been made for the general case the application ceases.

Yours truly,
W. H. INGRAM

(New York, N. Y.; Member, American Mathematical Society)

# Personal Items

**H. B. Dates** (A'98, F'32) will retire as head of the department of electrical engineering at Case School of Applied Science, Cleveland, Ohio, July 1, 1939, with the title of professor emeritus. Born in New Britain, Conn., July 15, 1869, he received the degree of bachelor of science in electrical engineering from Massachusetts Institute of Technology in 1894, and the honorary degree of electrical engineer from Case School in 1908. For two years after graduation he was employed by Westinghouse Electric and Manufacturing Company at Newark, N. J., and East Pittsburgh, Pa., before becoming professor of physics and electrical engineering at the newly established Clarkson School of Technology, Potsdam, N. Y., where he remained until 1903. For the two following years he was professor of electrical engineering and dean of the engineering school of the University of Colorado, Boulder, and in 1905 he became head of the Case School electrical-engineering department, where he has continued ever since. He has also carried on a consulting practice in electrical engineering, and has been a consultant for the Cleveland Board of Education and others on school lighting. He is a member of the AIEE committee on the production and application of light, and was the first chairman (1907–08) of the Cleveland Section. He is a past-president of the Illuminating Engineering Society, a member of the International Commission on Illumination, the National Electric Light Association, the Society for Promotion of Engineering Education, and Sigma Xi, and the author of many technical articles.

**H. E. Dexter** (A'14, M'17) has been appointed vice-president in charge of commercial relations by the Central Hudson Gas and Electric Corporation, Poughkeepsie, N. Y. Born at Randolph, Mass., in 1890, he received the degree of bachelor of science in electrical engineering from Massachusetts Institute of Technology in 1912, and entered the testing department of the General Electric Company, Schenectady, N. Y., the same year. He continued with that company until 1917, when he entered the United States Army, serving as a lieutenant in the engineering service. After the war he went to Shanghai, China, as engineering sales representative of Anderson, Meyer, and Company, continuing as manager of the Foochow office, and later at the Hongkong office of Anderson, Meyer, and Company, Ltd. Returning to the United States, he became refrigeration engineer, and then president of the Ideal Heating Company, Kansas City, Mo. For a time he was chief of the electrical equipment division, United States Bureau of Foreign and Domestic Commerce, Washington, D. C. He was first employed by the Central Hudson corporation as assistant commercial manager, becoming general commercial manager, and later, in 1935, a director of the company. He is chairman of the general sales committee of the Edison Electric Institute.

**M. W. Smith** (A'20, M'36) manager of engineering of the Westinghouse Electric and Manufacturing Company, with headquarters in Pittsburgh, Pa., has been elected a vice-president of the company. He will direct all engineering activities. A native (1893) of Overton, Tex., Mr. Smith graduated from Texas Agricultural and Mechanical College in 1915 with the degree of bachelor of science in electrical engineering. He then entered the student apprentice course at the Westinghouse company's East Pittsburgh works, and has remained with the company continuously ever since. He has been associated with generating engineering operations, first as a design engineer, then a section engineer (1926), then division engineer in charge of the design of large a-c machines (1930). In 1936 he was appointed manager of engineering. He received the Westinghouse Order of Merit award in 1938. He is a member of AIEE membership, publication, and technical program committees, and a member of the American Association for the Advancement of Science.

**J. W. Latham** (A'27) has been appointed chief engineer of the Chesapeake and Potomac Telephone Company of Baltimore City, Md. A native (1886) of Hickory Grove, Va., Mr. Latham is a graduate of the University of Virginia. He was employed in the engineering and installation departments of the Western Electric Company, Chicago, Ill., in 1906, and transferred the following year to the engineering department of the Chicago Telephone Company. He became an engineering inspector for the Southern Bell Telephone and Telegraph Company, Atlanta, Ga., in 1909 continuing with that company as division traffic supervisor, first in Charlotte, N. C., then in Savannah, Ga.; traffic equipment engineer, Atlanta, exchange traffic and operating practice engineer, Atlanta. In 1920 he entered the engineering department of the Chesapeake and Potomac Telephone Company, Washington, D. C., and shortly afterward was appointed facilities engineer. He later became chief engineer for the Chesapeake and Potomac Telephone Company of West Virginia, and held that position until his recent appointment.

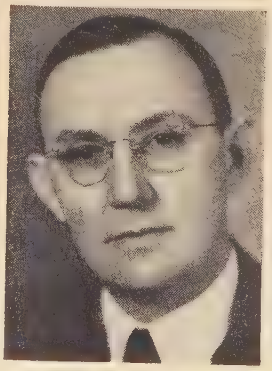
**M. M. Kenneally** (A'29) has been appointed vice-president in charge of sales of the Porcelain Insulator Corporation, Lima, N. Y. A native (1894) of Oelwein, Iowa, Mr. Kenneally received the degrees of bachelor of science in electrical engineering, 1915, and electrical engineer, 1920, from Iowa State College. During the World War he was an engineering officer in the United States Navy. In 1919 he became distribution survey engineer for the Waukesha (Wis.) Gas and Electric Company, and during the next eight years was employed in various engineering and executive capacities by the Citizens Gas and Electric Company, Waterloo, Iowa; the Philadelphia Suburban Gas and Electric Company, Jenkintown, Pa.; the Iowa Public Service Company, Humboldt; and the United Gas Improvement Company, Philadelphia, Pa., and on distribution surveys for the cities of Belleville and Kewanee, Ill. In 1927 he was employed by the Ohio Insulator Company, Barberton, and in 1928 became sales manager of the New York office of the Ohio Brass Company. Three years later he was transferred to Mansfield, Ohio, as sales manager of the power utilities department of that company. He became sales manager of the Porcelain Insulator Corporation in 1937.

**F. B. Jewett** (A'03, F'12) vice-president of the American Telephone and Telegraph Company and president of Bell Telephone Laboratories, Inc., New York, N. Y. has been elected president of the National Academy of Sciences. He was also honored recently for his scientific attainments by the

M. M. KENNEALLY

H. E. DEXTER

M. W. SMITH



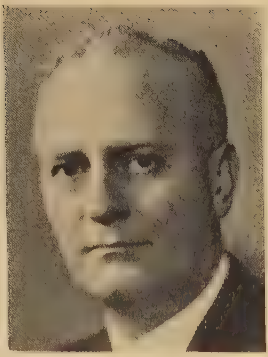
J. W. LATHAM

F. B. JEWETT

A. C. STREAMER

B. K. BOYCE

J. R. READ


R. H. HUGHES

R. B. MAC GUINNESS

presentation of the 1939 John Fritz Medal. An article outlining his qualifications for that award appeared in the March 1939 issue (pages 115–17), and a biographical sketch in the December 1938 issue (page 521).

**W. R. G. Baker** (A'19) has been appointed manager of the General Electric Company's newly organized radio and television department, with headquarters at Bridgeport, Conn. The new unit will co-ordinate all radio, television, and related activities. Doctor Baker has been engaged in radio development work since 1917. A native (1891) of Lockport, N. Y., he attended Union College, from which he holds the degrees of bachelor of engineering, master of electrical engineering, and doctor of science. Before entering the General Electric laboratories in 1917 he was employed by the New York Telephone Company. In 1924 he was placed in charge of design of all radio products for General Electric, and in 1926 he was given complete charge of radio development, design, and production. On formation of the RCA-Victor Corporation in 1929 he was made head of radio engineering activities, and later general manager of the plant at Camden, N. J. He resumed his connection with General Electric in 1936, becoming managing engineer of the radio receiver section at Bridgeport. Before his recent appointment he was chairman of the radio management committee.

**J. R. Carson** (A'19, F'33) research mathematician, Bell Telephone Laboratories, Inc., New York, N. Y., has been awarded the Elliott Cresson Medal by the Franklin Institute, Philadelphia, Pa., "in consideration of outstanding contributions to the art of electrical communication." A native (1887) of Pittsburgh, Pa., Mr. Carson received the degrees of bachelor of science (1907), electrical engineer (1909), and master of science (1912) from Princeton University. He was an instructor in physics and electrical engineering at Princeton University, Princeton, N. J., from 1912 to 1914, when he was employed in the engineering department of the American Telephone and Telegraph Company. He was transferred to the department of development and research in 1917, with the title of transmission theory engineer, and assumed his present position in the Bell Laboratories in 1934. He received in 1924 the Liebmann Memorial Prize of the Institute of Radio Engineers, of which he is a member. He is also a member of the American Mathematical Society and Phi Beta Kappa, and has written books and articles on technical subjects.

**B. K. Boyce** (A'10, M'28) has been appointed chief engineer, Manhattan area, by the New York Telephone Company. A native (1886) of Little Valley, N. Y., Mr. Boyce graduated in electrical engineering at Cornell University in 1907, and has been with the New York Telephone Company ever since. He was engaged in special studies on electrolysis, inductive disturbances, and protection, from 1907 to 1912, and on transmission work, including design, 1912–24. During the next two years he did plant extension work, becoming transmission and plant extension engineer in 1925. In 1926 he was appointed chief engineer for the upstate New York area, and continued in that position until his present appointment. He was a member of the AIEE committee on communication 1930–31.

**J. R. Read** (A'04) has been elected president of Canadian Westinghouse Company, Ltd., Hamilton, Ont., Canada. Born in Virginia October 24, 1879, Mr. Read began his electrical engineering experience with the Sterling White Lead Company, Parnassus, Pa., afterward spending three years as a student engineer with the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. He was employed as engineer by the Cherokee Gold Dredging Company, and the Northern California Power Company before entering the employ of Canadian Westinghouse in 1904 as sales engineer for the Vancouver district office. He was appointed district manager of the Vancouver district in 1908, was made a vice-president in 1936, and a director of the company in 1938.

**R. H. Hughes** (A'20, M'30) has been appointed vice-president and general manager of the Bronx-Westchester area of the New York (N. Y.) Telephone Company. He had been an assistant vice-president since 1927. A native (1891) of Decatur, Ala., Mr. Hughes graduated from Vanderbilt University in 1913, with the degree of bachelor of engineering. He has been with the New York Telephone Company continuously since 1914, when he entered the engineering department. He became a local trunk engineer in 1925, and plant extension engineer in 1927.

**A. C. Streamer** (A'10) has been appointed general manager of the East Pittsburgh division of the Westinghouse Electric and Manufacturing Company. He was formerly manager of the switchgear division of the East Pittsburgh works of the company. After graduating from the University of Colorado in 1907 with the degree of bachelor of science in electrical engineering, Mr. Streamer entered the apprentice engineering course of the Westinghouse company at East Pittsburgh, and was later assigned to the switchboard engineering division. He was made manager of the diversified products department in 1931, and manager of the switchgear division on its formation in 1936.

**R. B. MacGuinness** (A'09) has been appointed vice-president in charge of operations by the Central Hudson Gas and Electric Corporation, Poughkeepsie, N. Y A native (1883) of New York, N. Y., Mr. MacGuinness was employed in various capacities by the Westchester Light Company from 1901 to 1908, when he was placed in charge of the electrical department of Russell Birdsall and Ward Bolt and Nut Company, Port Chester, N. Y. He continued with that organization until his employment by the Central Hudson corporation in 1923 as division superintendent. He has been operating manager since 1926 and a director since 1932.

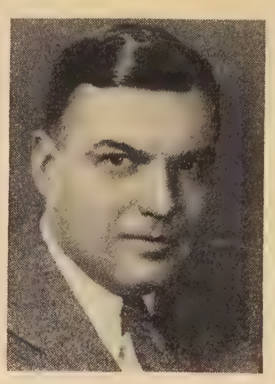
**G. H. Bucher** (M'24) president, Westinghouse Electric and Manufacturing Company and Westinghouse Electric International Company, was awarded the Westinghouse Order of Merit in 1938. A native (1888) of Sunbury, Pa., Mr. Bucher attended Pratt Institute and became associated with the Westinghouse company as a student engineer in 1909. The Order of Merit, founded in 1935, is awarded Westinghouse employees for outstanding contributions to the electrical and mechanical arts and to company progress. Other AIEE members to receive the award in 1938 are: **M. W. Smith** (A'20, M'36), recently appointed vice-president in charge of engineering, Pittsburgh, Pa.; **G. W. Penney** (A'26), manager,

electrophysics division, research laboratories; **C. M. Laffoon** (A'24) manager, a-c generator engineering department; **J. B. MacNeill** (A'18, M'36) manager, switchgear engineering; **D. F. Miner** (M'34) manager, engineering laboratories and standards; **J. S. Parsons** (A'27) central station engineer; **F. B. Powers** (M'37) engineering manager, transportation department; **I. B. Stiefel** (A'18) manager of industrial relations; all at East Pittsburgh, Pa.; **J. K. Hodnette** (A'25, M'30) transformer development engineer, Sharon, Pa.; **A. W. Copley** (A'04, F'26) engineering manager, Pacific Coast district, San Francisco, Calif.

**Barry Dibble** (A'06, M'12) has been appointed assistant administrator of the Bonneville Dam project, Portland, Ore. He was formerly a consulting electrical engineer for the United States Indian Service. A native (1881) of St. Paul, Minn., Mr. Dibble graduated in electrical engineering from the University of Minnesota in 1903. He was employed in engineering capacities by the Jackson and Battle Creek Traction Company, Albion, Mich., the Cincinnati and Columbus Traction Company, Cincinnati, Ohio, the Shawinigan Water and Power Company, Shawinigan Falls, Quebec, Can., and the Twin City Rapid Transit Company, St. Paul, Minn., before entering the service of the United States Government as an electrical engineer in the Reclamation Service. He was a construction engineer and later project manager of the Minidoka (Idaho) project, and later had headquarters in Denver, Colo. For more than ten years he has been in consulting practice, with offices at Redlands, Calif.

**P. L. Hoover** (A'24) has been appointed professor of electrical engineering and head of the electrical engineering department of Case School of Applied Science, Cleveland, Ohio. A native (1898) of Mansfield, Ohio, Doctor Hoover received the degree of bachelor of science at Carnegie Institute of Technology, and the degrees of master of science and doctor of science from Harvard University, where he was for three years a research fellow in electrical engineering. He has also studied at the Universities of Vienna and Paris. He was appointed associate professor of electrical engineering at Case School in 1927, continuing in this position until 1930, when he became assistant director of the engineering experiment station at Rutgers University, New Brunswick, N. J. In 1934 he was made director of the station with the rank of professor. He is a member of the American Physical Society, the American Association for the Advancement of Science, Sigma Xi, Gamma Alpha, and Tau Beta Pi, and is the author of various technical articles.

**J. S. Jones** (A'19, F'25) has been made manager of the western division, American Machine and Metals, Inc., San Francisco, Calif. A native (1888) of Norfolk, Va., Mr. Jones attended the Naval Apprentice School at the Norfolk Navy Yard, where he was afterward employed from 1909 to 1911. In 1911 he became an electrical draftsman at the Navy Yard, New York, N. Y., where he advanced through successive positions to that of senior electrical aide and acting electrical superintendent of the Third Naval District in 1918. In 1919 he went with Charles Cory and Son, Inc., New York, as assistant to the vice-president and engineer, and in 1923 became vice-president, general manager, and director of engineering of that company. Later he became assistant to the president, Consolidated Laundries Corporation, New York, then vice-president of American Machine and Metals, Inc., Washington, D. C. He left that organization to become vice-president of Stewart and McGuire, Inc., New York, for two years before returning to assume his present position.



J. B. HARRIS, JR.

**J. B. Harris, Jr.** (A'17) has been appointed vice-president of the Rumsey Electric Company, Philadelphia, Pa. A biographical sketch of Mr. Harris appeared in the May issue (page 228).

**G. A. Sawin** (A'03, M'13) has been appointed director of the regulatory legislation department of the National Electrical Manufacturers Association, with headquarters in New York, N. Y. He was formerly assistant manager, central station sales, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., and an associate representative of the Westinghouse company on the electrical instrument and transformer sections and the rural electrification publicity subcommittee of the NEMA. A graduate (1901) in electrical engineering at Harvard University, Mr. Sawin was employed by the General Electric Company, Lynn, Mass., and the Public Service Electric Company, Newark, N. J., before his association with the Westinghouse company.

**C. T. Hughes** (A'20, M'29) has been appointed general operating superintendent of the Connecticut Light and Power Company, Hartford. Born (1894) in Wickliffe, Ky., Mr. Hughes graduated from the University of Oklahoma in 1918 with the degree of bachelor of science in electrical engineering. He spent several months in the Signal Corps of the United States Army, and in December 1918 was employed by the Connecticut Light and Power Company as an assistant electrical engineer. He has been with the company continuously since that time, as electrical engineer and design engineer, and until his recent appointment, general engineer, with headquarters at Waterbury, Conn.

**M. G. Lloyd** (A'08, F'12) chief of the section of safety codes of the National Bureau of Standards, Washington, D. C., has been elected president of the International Association of Electrical Inspectors. Doctor Lloyd, who holds the degrees of bachelor of science (1896), doctor of philosophy (1900), and electrical engineer (1908), from the University of Pennsylvania, has occupied his present position with the Bureau of Standards since 1917. He is a member of the AIEE committees on safety and protective devices, and past chairman of the Washington Section. He is president of the Washington (D. C.) Safety Society and member of a number of other technical organizations.

**Roy Martindale** (M'21) has been appointed electrical engineer in charge of operations for the Bureau of Power and Light of the City of Los Angeles, Calif. A native (1884) of Attica, Ind., he received the degree of bachelor of science in electrical engineering from Purdue University in 1906, and during the following year was a student engineer for General Electric Company, Schenectady, N. Y. From 1908 to 1911 he was employed on power projects by the Washington Water Power Company, Spokane, Wash. He has been with the Los Angeles Bureau of Power and Light since 1911, assuming in 1920 the position of assistant operating engineer which he held until his recent appointment.

**C. W. Green** (A'10, M'26) has been appointed technical representative in Europe for the Bell Telephone Laboratories, Inc. Born in 1884 in Waukegan, Ill., Mr. Green graduated in 1907 from the University of Wisconsin, with the degree of bachelor of science. He was an instructor in electrical engineering at Massachusetts Institute of Technology, Cambridge, from 1907 to 1914 and assistant professor, 1914–17. During the World War he served in the United States Coast Artillery, attaining the rank of major. He became a telephone engineer for Western Electric Company, New York, N. Y., in 1919, and transferred to the Bell Laboratories in 1924.

**L. F. Pries** (A'33) with two partners, has organized Central States Industrial Engineers, DeKalb, Ill., designers and builders specializing in production machinery for the wire industry. A native (1907) of Buffalo, N. Y., Mr. Pries received the degrees of electrical engineer, 1931, and master of electrical engineering, 1932, from Rensselaer Polytechnic Institute. After graduation he was employed by the Colonial Radio Corporation, Buffalo, as a development engineer by the Wurlitzer Grand Piano Company, DeKalb, Ill., and in the engineering department of the DeKalb plant of the American Steel and Wire Company.

**H. R. Peddicord** (A'38) has been appointed general buildings and supplies superintendent, Chesapeake and Potomac Telephone Company, Washington, D. C. A native (1900) of Cooksville, Md., Mr. Peddicord received the degree of bachelor of science in electrical engineering from the University of Maryland in 1921. He spent a year in the student course of the Westinghouse Electric and Manufacturing Company East Pittsburgh, Pa., and a year teaching mathematics in New York, N. Y. Since 1923 he has been with the Chesapeake and Potomac company. From 1936 until the present he had the position of engineer.

**R. L. Horr** (M'26) has been appointed general plant engineer by the Mountain States Telephone and Telegraph Company, Denver, Colo. Mr. Horr is an electrical engineering graduate of the University of Illinois (1904), and was employed in maintenance and inspection work by the Chicago (Ill.) Telephone Company 1904–14. During the next two years he was chief engineer for the Montana Fruit and Irrigation Company, after which he spent four years in business. He has been with the Mountain States company since 1920, and before his present appointment was general plant supervisor.

**R. C. Muir** (A'08, M'19) vice-president in charge of engineering, General Electric Company, Schenectady, N. Y., will be awarded the honorary degree of doctor of engineering by the University of Wisconsin at its 1939 commencement exercises. Mr. Muir is a graduate of the University of Wisconsin, having received the degree of bachelor of science in electrical engineering in 1905. He entered the General Electric student engineering course at Schenectady the same year, and has been with the company ever since, assuming his present position in 1934.

**R. P. Long** (A'34) has been appointed general plant employment supervisor, eastern district, Bell Telephone Company of Pennsylvania, Philadelphia, Pa. After graduating in electrical engineering from Cornell University in 1921, Mr. Long entered the employ of that company, later becoming plant transmission engineer. Before his recent appointment he was district plant superintendent.

**J. E. M. Mitchell** (A'27) has been appointed assistant sales manager of Porcelain Products, Inc., Parkersburg, W. Va. He was formerly general sales manager, Jeffery-DeWitt Insulator Company, Kenova, W. Va., having been associated with that company since 1924, and prior to that was a sales engineer with W. K. Beaven, Birmingham, Ala.

**G. R. Mezger** (A'37) has been appointed assistant sales manager on industrial sales of television equipment by the Allen D. DuMont Laboratories, Inc., Passaic, N. J. A graduate in electrical engineering of Rensselaer Polytechnic Institute, Mr. Mezger has been a research and development engineer for the DuMont Laboratories since 1936.

**A. E. Kennelly** (A'88, F'13, HM'33) has been elected a member of the Royal Academy of Sciences of Upsala, Sweden. Doctor Kennelly is professor emeritus of electrical engineering at Harvard University and Massachusetts Institute of Technology, and AIEE past-president and Edison Medalist (1933). A biographical sketch of him appeared in the October 1938 issue (page 433).

**E. E. Wyland** (A'29) has been appointed general plant supervisor, Mountain States Telephone and Telegraph Company, Denver Colo. A graduate of the University of Idaho, Mr. Wyland has been with the company since 1924, much of the time in the transmission department. Before his present appointment he was acting Idaho plant superintendent.

**P. A. Condit** (A'37) has been employed as a control engineer by the Cooper-Bessemer Corporation, Mount Vernon, Ohio. He was formerly in charge of development and field engineering for the Mason-Neilan Regulator Company, Boston, Mass.

**R. H. Manahan** (M'22) chief, electrical division, Department of Building and Safety, City of Los Angeles, Calif., has been appointed chairman of the legislative committee, southwestern district, International Association of Electrical Inspectors.

**E. S. McConnell** (A'29, M'36) formerly electrical engineer for Anaconda Wire and Cable Company, New York, N. Y., is now with the Copper Wire Engineering Association, Washington, D. C., as electrical engineer.

**R. O. Froling** (A'37) has been employed as an engineer in the vibration department of the propeller division of the Curtiss Wright Corporation, Clifton, N. J. He was formerly a student engineer with the General Electric Company, at Pittsfield, Mass.

**O. G. Owens** (A'38) has been appointed an instructor in the university extension division, Rutgers University, New Brunswick, N. J. He was formerly a student physicist at General Electric Company, Lynn, Mass.

**R. S. Brannin, Jr.** (A'37) formerly a logging operator for the Humble Oil and Refining Company, Houston, Tex., has been employed by the Lago Petroleum Corporation, Maracaibo, Venezuela.

**W. F. Sims** (A'20, F'33) chief electrical engineer, Commonwealth Edison Company, Chicago, Ill., has been elected a director of the Electric Association of Chicago, to complete the 1939–40 term.

**H. V. Dobson** (A'28) city electrician, City of Santa Barbara, Calif., has been appointed chairman of the articles of association committee, southwestern district, International Association of Electrical Inspectors.

**A. R. Small** (M'37) president, Underwriters Laboratories, Chicago, Ill., was elected a vice-president of the National Fire Protection Association at its recent annual meeting.

**C. C. Curtis** (M'23) president, Savannah Electric and Power Company, was elected third vice-president of the Southeastern Electric Exchange at its recent annual convention at St. Augustine, Fla.

**A. D. Bragg** (A'36), sales representative, General Electric Company, Fresno, Calif., has been elected president of the Engineers Club of Fresno.

**P. A. Ward** (A'37) field engineer, air conditioning department, General Electric Company, has been transferred from Chicago to the Detroit office of the department.

**L. L. Lathrop** (A'35) has been transferred by the New York Power and Light Company from Schenectady to Mahopac, N. Y., where he is operator of the Carmel substation.

## Obituary

**Albert Gould Davis** (A'98, M'00, F'12) patent lawyer and former vice-president in charge of patents of the General Electric Company, died in New York, N. Y., April 25, 1939. Born October 19, 1871, at Brooklyn, N. Y., Mr. Davis was graduated in electrical engineering from Massachusetts Institute of Technology in 1893, and received the degrees of bachelor and master of laws in 1896 and 1897, respectively, from the National University law school, Washington, D. C. In 1893–94 he was in charge of design and construction of furnaces for the Davis-Colby Ore Roaster Company, in Kentucky and Alabama. He became an assistant examiner in the United States Patent Office, Washington, D. C., in 1894, leaving that position in 1896 to engage in private patent-law practice. In 1897 he was made manager of the patent-law department of the General Electric Company, Schenectady, N. Y., and continued in that position until 1919 when he was made vice-president in charge of patents. Shortly after the incorporation of the Radio Corporation of America in 1919, Mr. Davis became a director of that organization, having had an active part in the negotiations by which the Marconi Wireless Telegraph Company of America acquired assets and patents, later purchased by RCA, from its parent company, Marconi's Wireless Telegraph Company, Ltd., London, England. He remained a director until the relationship between General Electric and RCA was dissolved in 1932. The following year he retired from the General Electric Company and became a consulting member of the firm of Pennie, Davis, Marvin, and Edmonds, New York, N. Y. From 1937 until his death he was engaged in independent law practice at 30 Rockefeller Plaza, New York, N. Y. He was president of the New York State Patent Law Association and a member of several other legal organizations.

**John Jameson Gibson** (A'02, M'12, F'18) retired vice-president, Westinghouse Electric Supply Company, New York, N. Y., died in Philadelphia, Pa., May 6, 1939. Born in York, Pa., November 23, 1872, he graduated from Lehigh University in 1895 with the degree of electrical engineer, and entered the student course at Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. In 1896 he was employed by the American Telephone and Telegraph Company as inspector in the New York district, then as manager of the seventh district with headquarters at Norfolk, Va., and by the Southern Bell Telephone and Telegraph Company as manager of the Richmond and later the Norfolk district. In 1900 he returned to the Westinghouse company as manager's assistant in the Chicago office, where he later became sales engineer and manager of the industrial division. He was transferred to the Philadelphia office in 1905 as sales engineer, and was district manager 1906–14. In 1915 he was appointed manager of the supply department of the company at East Pittsburgh, and continued in that position until 1922, when he became vice-president and general manager of Westinghouse Commercial Investment Company, New York, N. Y. The latter organization developed into the present Westinghouse Electric Supply Company, with which Mr. Gibson continued in the same capacity until his retirement in 1932. After retirement he was president of the Cresheim Arms Company, managing the hotel of that name in Philadelphia. He was a member of the Franklin Institute, Philadelphia, and had served on its board of managers.

**Herbert William Crozier** (A'03, M'12) consulting engineer, died at Covina, Calif., April 13, 1939. Born at San Francisco, Calif., June 28, 1875, he graduated from the University of California in 1899 with the degree of bachelor of science. He was employed in engineering capacities by the Harvard Mine, Jamestown, Calif., the Tuolumne County (Calif.) Water Company, and the Cananea Consolidated Copper Company, Cananea, Mex., until 1902, when he became an electrical engineer for the department of electricity of the City of San Francisco. Later he engaged in construction work on the staff of R. S. Masson, electrical engineer, on the Pacific Electric Railway, and other lines, and then became associated with the consulting engineering firm of Sanderson and Porter, San Francisco, Calif., later becoming manager of the San Francisco office of the firm. During the latter years of his life he was an independent consulting engineer, with offices in San Francisco and later in Las Vegas, Nev. He was connected with a number of governmental power projects, being consulting engineer for the state of Nevada, 1923–26, for the Nevada Colorado River Commission, 1927–28, the Central Valley project, 1935, and supervising the design and construction of the power line from Boulder Dam to the Pioche mining region of Nevada, 1936–37. He was a member of the American Society of Mechanical Engineers.

**Edouard Roth** (A'18) chief engineer of technical services of La Société Générale de Constructions Électriques et Méchaniques, "Alsthom," Paris, France, died April 29, 1939. He was born at Mulhouse, Alsace, January 17, 1878, and graduated from the École Polytéchnique Féderale, Zurich, Switzerland, in 1900. The same year he entered the technical service of the Société Alsacienne de Constructions Méchaniques at Belfort, and later became chief engineer for a-c apparatus. He assumed the position which he held until his death when the Société Alsacienne consolidated with the Compagnie Française–Thomson Houston to form the "Alsthom" organization during the 1920's. Mr. Roth was responsible for many important turbine-generator installations in Paris and other French cities. He was a member of the Société Française des Électriciens, and was active in the International Electrotechnical Commission, serving on various committees, and in other ways participating in international standardization activities. He was the author of many technical papers and articles, and made important contributions to the design and construction of electrical machinery. He was a Chevalier of the Legion of Honor, and had received the silver medal of the Industrial Society of Mulhouse, the Hebert prize of the French Academy of Science (1925), and other honors and awards for his work.

**Emmet Grattan Ralston** (A'21, M'34) vice-president and general manager of the Indianapolis Power and Light Company, Indianapolis, Ind., died April 17, 1939. He was born in Lebanon, Ind., October 28, 1890, and graduated from Purdue University with the degree of bachelor of science in electrical engineering, in 1913. The same year he was employed by the Indianapolis Light and Heat Company, first as a meter tester, then in charge of demand testing. He continued with that company as underground superintendent, design engineer, chief engineer of Mill Street station, electrical superintendent, chief engineer, and operating vice-president. He remained in the last position when the company, as the result of a merger, became the Indianapolis Power and Light Company, and in 1930 became a member of the board. He had held the position of vice-president and general manager for about three years. He was a member and former president of the National Association of Power Engineers and also of the Indiana Electric Association, and at the time of his death was president of the Indianapolis Electric League.

**William Cramp** (M'26) professor of electrical engineering at the University of Birmingham, England, died April 20, 1939, at Llandudno, Wales. Born January 8, 1876, at Coventry, England, he received the degrees of master of science at the College of Technology, Manchester, and doctor of science at the University of Manchester. He was an engineer apprentice from 1892 to 1897, when he became assistant to the works manager of Ferranti, Ltd., Hollinwood. In 1900 he was appointed lecturer in electrical design at the Imperial College of Science and Technology, London. From 1905 to 1920 he was a member of the firm of Cramp and Frith, consulting engineers, Manchester, and also acted as a lecturer in electrical design and technology at the University of Manchester. He was appointed professor of electrical engineering at the University of Birmingham in 1920. Professor Cramp was the author of books and articles on technical subjects, and a member of the Institution of Electrical Engineers, having served on the council of that society.

**Emerson Pierce Peck** (A'08, M'20, F'23) consulting engineer, Buffalo, Niagara, and Eastern Power Corporation, Buffalo, N. Y., died November 14, 1938, according to information recently received. Mr. Peck was born at Atlanta, Ga., August 13, 1882, and studied at the Georgia School of Technology. In 1905 he was employed by the Georgia Railway and Electric Company, Atlanta, and in 1906 became foreman of the testing department, in 1914 superintendent of tests and repairs department, and in 1916 superintendent of operation. In 1918–19 he served as a technical expert for the United States Bureau of Standards and the War Department. He became general superintendent of the electrical department, Utica (N. Y.) Gas and Electric Company in 1919, later becoming a vice-president of the company. Subsequently he became associated with the New York Power and Light Company, Albany, N. Y., as an engineer on special studies, and was later employed in the same capacity by the Buffalo, Niagara, and Eastern Power Corporation.

**Loren H. Shute** (A'15) superintendent, electrical division, Light and Power Department of the City of Colorado Springs Colo., died in Agua Caliente, Ariz., February 10, 1939. He was born in Denver, Colo., October 1, 1883, and attended high school there, afterward being employed in the shops of the Denver Gas and Electric Company 1902–05. For the next four years he was engaged in installing electrical and mining machinery for the Yak Mining, Mill and Tunnel Company, Leadville, Colo. In 1908 he was employed by the Central Colorado Power Company, Denver, on construction and transmission work, becoming superintendent of operations in 1912 and general superintendent of all properties in 1914. He continued in the last-named position until 1922, when he moved to California on account of health. In 1924–25 he was a line specialist for Western Electric Company, Denver, Colo., and in 1925 he assumed the position at Colorado Springs which he held until his death.

**Thomas Hesketh** (A'04, M'06) director, Folkestone Electricity Supply Company, Ltd., Folkestone, England, died in March 1939. He was born at Lytham Lanes, England, April 19, 1873, and educated at the Durham College of Science, Newcastle-on-Tyne. He later served an apprenticeship of three years with J. H. Holmes and Company of the same city. In 1892 he was appointed chief engineering assistant at the Blackpool (Eng.) Electricity Works, and in 1895 took the position of electrical engineer at the electric light plant of Madrid, Spain. He was appointed engineer and manager of the Folkestone Electricity Supply Company in 1898, having charge of the design and construction of the station and later managing it. In 1923 he became managing director of the company, and later director. He was a member of the Institution of Electrical Engineers and the Institution of Mechanical Engineers, both of Great Britain.

**Ernest Joseph Sterba** (A'21, M'35) member of the technical staff, Bell Telephone Laboratories, Inc., New York, N. Y., died

April 24, 1939, at Asbury Park, N. J. He was born in Iowa City, Iowa, June 29, 1896, and received the degree of bachelor of engineering in electrical engineering from the University of Iowa, where he was an assistant instructor of physics in 1919–20. During 1920 he was a research engineer for Western Electric Company, New York, N. Y., and from that time until his death was engaged in research and development of radio transmission equipment for the Bell Laboratories. He was a member of the Institute of Radio Engineers and author of many technical articles.

**William Sterling Fields** (A'25) senior power engineer, American Rolling Mill Company, Ashland, Ky., died March 9, 1939. He was born March 9, 1901, at Sadieville, Ky., and received the degree of electrical engineer from the University of Cincinnati in 1924. From 1918 to 1924 he was employed in various capacities by the Union Gas and Electric Company, Cincinnati, Ohio. In 1924 he became supervisor of tests and power distribution for the American Rolling Mill Company, later becoming technician in the electrical power department, and senior power engineer, the position which he held at the time of his death.

**Albert Rolaz Gallatin** (A'98) member of the brokerage firm of Smith and Gallatin, New York, N. Y., died in March 1939. Born in New York October 4, 1869, he received the degree of bachelor of arts in 1891 from Columbia University, where he later studied electrical engineering. He was associated with Smith and Gallatin for more than 30 years.

# Membership

## Recommended for Transfer

The board of examiners, at its meeting on May 18, 1939, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

### To Grade of Fellow

Keath, H. B., engineer, in charge of transformer div. Wagner Electric Corporation, St. Louis, Mo.
Lisberger, S. J., chief, division of electric distribution, Pacific Gas and Electric Company, San Francisco, Calif.
Milburn, L. R., electrical engineer, Great Lakes Steel Corporation, Detroit, Mich.
Stein, I. Melville, director of research, Leeds and Northrup Company, Philadelphia, Pa.

4 to Grade of Fellow

### To Grade of Member

Bass, J. H., equipment engineer, Southwestern Bell Telephone Company, Oklahoma City, Okla.
Black, R. A., foreign trade manager, Ohio Brass Company, Mansfield.
Briggs, A. F., assistant electrical superintendent, Sun Oil Company, Beaumont, Tex.
Chase, D. D., central station department, General Electric Company, Schenectady, N. Y.
Christenbury, F. L., superintendent of meter and relay division, Memphis Power and Light Company, Memphis, Tenn.
Embree, J. N., assistant distribution engineer, Union Electric Company of Missouri, St. Louis.
Harkins, J. M., electrical engineer, Hydroelectric Power Commission of Ontario, Toronto, Ont., Can.
Henderson, M. L., electrical engineer, General Electric Company, Pittsfield, Mass.
Ibach, W. R., assistant customer's substation engineer, Wisconsin Electric Power Company, Milwaukee.
Jones, J. L., plant supervisor, Southwestern Bell Telephone Company, Oklahoma City, Okla.
Kerrigan, A. L., electrical engineer, Fitchburg Gas and Electric Light Company, Fitchburg, Mass.
Laffoon, C. M., engineering manager, a-c generator engineering department, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
Lyons, S. H., building and equipment engineer, Southwestern Bell Telephone Company, Oklahoma City, Okla.
Malsbary, J. S., electrical engineer, Wagner Electric Corporation, St. Louis, Mo.
McCluskey, F. J., assistant chief engineer, James R. Kearney Corporation, St. Louis, Mo.
Michael, J. H., assistant engineer, Allis-Chalmers Company, Milwaukee, Wis.
Mollman, L. A., electrical engineer, Union Electric Company of Missouri, St. Louis.
Muir, A. C., electrical engineer, The Berwind-White Coal Mining Company, Philadelphia, Pa.
Poole, F. L., assistant professor of electrical engineering, University of Utah, Salt Lake City.
Prosser, R. A., electrical shop department head, Seneca Vocation High School, Buffalo, N. Y.
Robinson, C. P., synchronous division engineer, The Ideal Electric and Manufacturing Company, Mansfield, Ohio.
Sampson, C. L., engineer of transmission, protection and plant extension, Northwestern Bell Telephone Company, Des Moines, Iowa.
Summers, C. M., electrical engineer, General Electric Company, Fort Wayne, Ind.
Teague, W. L., engineer, Westinghouse Electric and Manufacturing Company, Sharon, Pa.
Timoshenko, Gregory S., instructor in electrical engineering, Massachusetts Institute of Technology, Cambridge.
Wells, F. J., junior engineer, New York and Queens Electric Light and Power Company, Flushing.
Whitlow, G. S., application engineer, General Electric Company, St. Louis, Mo.
Wyatt, K. S., technical director, Enfield Cable Works, Ltd., Middlesex, England.

28 to Grade of Member

## Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. Names of applicants in the United States and Canada are arranged by geographical Districts. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before June 30, 1939, or August 31, 1939, if the applicant resides outside of the United States or Canada.

### United States and Canada

1. NORTH EASTERN

Camerlengo, J. M., General Electric Company, Pittsfield, Mass.
Dickman, K. W., Harvard Business School, Boston, Mass.
Engel, G. W. (Member), International General Electric Company, Schenectady, N. Y.
Krishnan, L. M., Massachusetts Institute of Technology, Cambridge, Mass.
Ritter, J., Stromberg Carlson Telephone Manufacturing Company, Rochester, N. Y.
Rumsey, A. L. (Member), New York Telephone Company, Albany, N. Y.
Sutton, C. E., Jr., General Electric Company, Pittsfield, Mass.
Thompson, L. W., General Electric Company, Schenectady, N. Y.

2. MIDDLE EASTERN

Askey, J. S., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
Blair, C. J., Ideal Electric and Manufacturing Company, Mansfield, Ohio.
Blatt, R. C. (Member), care of Municipal Architect of the District of Columbia, Washington, D. C.
Brown, H. M., United States Patent Office, Washington, D. C.
Giles, M. A., Ohio Public Service Company, Mansfield, Ohio.
Langevin, L. J., Westinghouse Electric and Manufacturing Company, Cincinnati, Ohio.
McCabe, D. (Member), Davison Chemical Company, Baltimore, Md.
McLaughlin, J. W. M., National Defense Power Committee, Washington, D. C.

3. NEW YORK CITY (TERRITORY OF THE NEW YORK SECTION)

Alford, A., Mackay Radio and Telegraph Company, New York, N. Y.
Campbell, J. W. (Member), American Telephone and Telegraph Company, New York, N. Y.
Dunn, J. W. (Member), Public Service Electric and Gas Company, Newark, N. J.
Felch, E. P., Jr. (Member), Bell Telephone Laboratories, Inc., New York, N. Y.
Pease, R. M., Philco Radio and Television Corporation, New York, N. Y.
Plank, C. S. (Member), American Telephone and Telegraph Company, New York, N. Y.
Ruze, J., Signal Corps Laboratories, Fort Monmouth, N. J.
Swart, L. K., Bell Telephone Laboratories, New York, N. Y.
Whitmore, P. G. (Member), Ebasco Services Inc., New York, N. Y.

4. SOUTHERN

Blackburn, L. A. (Member), Slaughter Saville and Blackburn, Inc., Richmond, Va.
Mathews, W. E., Carolina Aluminum Company, Badin, N. C.

5. GREAT LAKES

Bartholomew, D., University of Minnesota, Minneapolis.
Blanchett, L. E., Bucyrus Erie Company, South Milwaukee, Wis.
Bullen, C. V., Barber-Colman Company, Rockford, Ill.
Hanna, R. C., General Electric Company, Fort Wayne, Ind.
Johnson, R. H., General Electric Company, Fort Wayne, Ind.
Kahler, W. V. (Member), Illinois Bell Telephone Company, Chicago, Ill.
Kilgour, A. E., Commonwealth and Southern Corporation, Jackson, Mich.
Poole, W. C. (Member), Sinclair Refining Company, East Chicago, Ind.
Schwandt, G. O., General Electric Company, Fort Wayne, Ind.
Stites, H. E., Commonwealth and Southern Corporation, Jackson, Mich.

6. NORTH CENTRAL

McCormick, H. T., 43 Blair Avenue, Rock Springs, Wyo.

7. SOUTH WEST

Bromagem, J., Southwestern Bell Telephone Company, Fort Worth, Tex.
Coryell, W. R., Jr. (Member), S. C. Sachs Company, St. Louis, Mo.
December, F. O., Houston Lighting and Power Company, Houston, Texas.
Farmer, L. L., Nevada Consolidated Copper Corporation, Hurley, N. Mex.
Gehm, E. S., Union Electric Company of Missouri, Webster Groves.
Glenn, V. T., Mid-west Electric Cooperative Association, Rotan, Texas.
Phinney, J. M., Black and Veatch, Kansas City, Mo.
Stonecipher, G. A., Mountain States Telephone and Telegraph Company, El Paso, Texas.

8. PACIFIC

Bertram, E. C., North American Aviation, Inc., Ingelwood, Calif.
Collins, I. W., Pacific Gas and Electric Company, Oakland, Calif.
Dutter, D. D., Southern California Edison Company, Ltd., Los Angeles, Calif.
Looper, F. B., Los Angeles Bureau Power and Light, Boulder City, Nev.
Lough, H. N., Southern California Edison Company, Ltd., Colton, Calif.
Muller, C. R., United States Navy Yard, Pearl Harbor, T. H.
Porter, J. C., General Electric Company, Los Angeles, Calif.
Shideler, J. H., Route 2, Box 330, Hemet, Calif.
Strong, R. T., Westinghouse Electric and Manufacturing Company, San Diego, Calif.
Thomas, W. C. (Member), Southern California Telephone Company, Los Angeles, Calif.

9. NORTH WEST

Arnett, H. E., Portland General Electric Company, Portland, Ore.
Canada, C. E. (Member), General Electric Company, Portland, Ore.
Wing, W. C., Pacific Telephone and Telegraph Company, Spokane, Wash.

10. CANADA

Lillie, H., Bruce Peebles and Company, Ltd., Montreal, Que.
Peebles, R. M., Canadian Westinghouse Company, Hamilton, Ont.
Smeaton, J. M., Dominion Cutout Company Toronto, Ontario, Canada.

Total, United States and Canada—62

### Elsewhere

Vegtery, A., Socony Vacuum Oil Company, Inc., Istanbul, Turkey.
Sarma, T. N. R., Poona Electric Supply Company Ltd., Poona, India.
Piazza, T. L., Compania Italo Argentina de Electricidad, Buenos Aires, South America.

Total, elsewhere—3

# Engineering Literature

## New Books in the Societies Library

Electrical engineers may be interested in the following new books, which are among those recently received at the Engineering Societies Library, New York, N. Y. Unless otherwise specified, books listed have been presented by the publishers. The Institute assumes no responsibility for statements made in the following summaries, information for which is taken from the preface of the book in question.

THEORY OF LUBRICATION. By M. D. Hersey. New York, John Wiley and Sons, 1938. 175 pages, diagrams, etc., 9 by 6 inches, cloth, $2.50. Aims to give a balanced picture of the scientific background of modern lubrication. The topics considered are viscosity, the hydrodynamical and dimensional theories, temperature rise in bearings, and the problem of oiliness. A section on recent developments has been added to this edition. Bibliographies accompany each section.

WATER SUPPLY ENGINEERING. By H. E. Babbitt and J. J. Doland. Third edition. New York and London, McGraw-Hill Book Company, 1939. 690 pages, illustrated, 9 by 6 inches, cloth, $6.00. A comprehensive introductory textbook presenting material on finances, hydraulics, ground water and wells, dams and mechanical equipment, electrical equipment, distribution systems, filtration, and the analysis, softening, and purification of water.

THE THEORY of MACHINES. By T. Bevan. London and New York, Longmans, Green and Company, 1939. 549 pages, diagrams, etc., 9 by 6 inches, cloth, $5.40. Following a brief résumé of the principles of elementary mechanics, the succeeding chapters deal with the various fundamental types of mechanisms, such as gears, cams, belt drives, etc., and discuss the subjects of vibration and balancing. To facilitate the graphical solution of problems, diagrams have been carefully drawn to scale. The answers to the problems given with the text are collected in the back of the book.

HYDRAULICS FOR ENGINEERS AND ENGINEERING STUDENTS. By F. C. Lea. Sixth edition. New York, Longmans, Green and Company, 1938. 757 pages, illustrated, 9 by 6 inches, cloth, $6.75. The opening chapters deal with the basic characteristics of fluids at rest and in motion. The several chapters following contain a detailed analysis of the flow of water over weirs, through orifices and pipes, and in open channels, as well as of gauging practice. A chapter on the impact of water on vanes is introductory to the description and analysis of water wheels, turbines, centrifugal and reciprocating pumps, and other hydraulic machines. Streamline motion and dynamical similarity are briefly discussed.

SPECIFICATION DOCUMENTS FOR BUILDING MATERIALS and CONSTRUCTION. Los Angeles, Calif., Pacific Coast Building Officials Conference, 1938. 386 pages, diagrams, etc., 8 by 5 inches, cloth, $4.00. The specifications in this volume form part of the Uniform Building Code of the Pacific Coast Building Officials Conference. They include those on building materials, standards of fire resistance, and building appurtenances and equipment published by various national engineering organizations and adopted by the Conference.

INCHLEY'S THEORY OF HEAT ENGINES. Edited and revised by H. W. Baker. New York and London, Longmans, Green and Company, 1938. 445 pages, diagrams, etc., 9 by 6 inches, cloth, $3.60. Considerably changed from the original book, this new edition retains the author's idea "to give in a complete and concise form the thermodynamical principles of the subject." Fundamental general principles and then the more specific applications are considered respectively before the discussion of devices: air compressors and motors, reciprocating steam engines, steam turbines, internal combustion engines, and mechanical refrigerators. Heat transfer, combustion, and test methods are also included.

INDEX TO ASTM STANDARDS AND TENTATIVE STANDARDS, January 1939. Philadelphia, Pa. American Society for Testing Materials, 1939. 129 pages, 9 by 6 inches, paper, free upon application. A convenient guide to the current state of standardization by the society, indexing all the specifications, test methods, and definitions now in force, regardless of the volumes in which they appear. Over 800 specifications are indexed under appropriate headings.

SECOND REPORT ON VISCOSITY AND PLASTICITY. Prepared by the Committee for the Study of Viscosity of the Academy of Sciences at Amsterdam. N. V. Noord-Hollandsche Uitgeversmaatschappij, Amsterdam; New York, Nordemann Publishing Company, 1938. 282 pages, illustrated, 11 by 7 inches, cloth, $7.50. The first report of this Committee appeared in 1935. The second report includes surveys of further developments treated in the first, and also a discussion of problems concerning the internal structure of liquids. Among the topics considered are the relation of the viscosity of liquids to their chemical and physical constitution, the motion of small elongated particles in a viscous liquid, the yield value, recent plastometers, and technical capillary viscosimeters.

TENSOR ANALYSIS OF NETWORKS. By G. Kron. New York, John Wiley and Sons, 1939. 635 pages, diagrams, etc., 9 by 6 inches, cloth, $7.50. Presents a new method of approach to the analysis and synthesis of networks through the use of tensors and spinors. Although the book deals specifically with the organization of those sets of linear, algebraic equations occurring in the study of asymmetrical active networks having lumped constants, it also constitutes an introduction to similar applications of tensor analysis in other engineering fields.

DIESEL ENGINES, THEORY AND DESIGN. By H. E. Degler. Chicago, American Technical Society, 1939. 270 pages, illustrated, 9 by 6 inches, cloth, $2.50. A practical elementary text which uses only elementary mathematics, intended for evening-school classes and home study. Thermodynamics, fuels and combustion, and testing are considered, together with the principles of design and the design of engine parts.

HIGHER MATHEMATICS. By R. S. Burington and C. C. Torrance. New York and London, McGraw-Hill Book Company, 1939. 844 pages, diagrams, etc., 9 by 6 inches, cloth, $5.00. Designed primarily for students interested in the applications of mathematics to physics and engineering, the concepts presented have been developed with sufficient rigor to be suitable as well for students of pure mathematics. In the following topics the physical meanings of the various notations and relationships have been emphasized, with the help of numerous examples and exercises: advanced differential and integral calculus; differential equations; infinite series; functions of a complex variable; vector analysis; and the calculus of variations.

LIGHT. By F. Bray. Second edition. London, Edward Arnold and Company; New York, Longmans, Green and Company, 1938. 369 pages, illustrated, diagrams, etc., 8 by 5 inches, cloth, $2.50. The field of optics is covered quite fully in this elementary textbook, the subject matter including the fundamental phenomena of propagation, reflection, and refraction, description of the eye and various optical instruments, and discussions of diffraction, polarization, and spectra. Questions with answers are included.

NUMBER, THE LANGUAGE OF SCIENCE. By T. Dantzig. Third edition. New York, The Macmillan Company, 1939. 320 pages, illustrated, 9 by 6 inches, cloth, $3.00. An account of the manner in which our concept of number has developed from finger counting into the modern science, written with a minimum of technicalities for the nonmathematically educated reader. A group of twenty-six short articles on technical, historical, and philosophical matters has been added in this edition.

THE FUNDAMENTALS OF ELECTROMAGNETISM. By E. G. Cullwick. Cambridge, England, University Press; New York, The Macmillan Company, 1939. 352 pages, illustrated, 9 by 6 inches, cloth, $4.50. Starting with electrostatics and continuing through permanent magnets to electro-magnetic waves, the theory of electromagnetism is here developed on the basis of demonstrable physical concepts, discarding, along with the unit magnetic pole, the attempt to establish and utilize an actual electro-magnetic field. Either the orthodox units or the new meter-killogram-second practical units may be applied. Many examples and problems are included.

PRACTICAL ELECTRIC ILLUMINATION AND SIGNAL-WIRING METHODS. By T. Croft. Revised by G. H. Hall. Third edition. New York and London, McGraw-Hill Book Company, 1939. 351 pages, illustrated, 8 by 6 inches, cloth, $3.00. Gives rules, methods, diagrams, and other data useful for many electrical jobs. In the illumination field will be found analyses of lighting requirements, design of circuits, and selection and installation of fixtures, including mercury and sodium vapor lamps. Methods for signal wiring work are given in line with Code requirements. Many signal circuit diagrams.

PHYSICAL SCIENCE IN MODERN LIFE. By E. G. Richardson. New York, D. Van Nostrand Company, 1939. 256 pages, illustrated, 8 by 5 inches, cloth, $3.00. An account intended for the general reader, of some recent developments in physics. The subjects chosen touch everyday existence. Streams and eddies, vibrations and waves, colloids, heat, light, electricity, sensation and reaction are among the matters considered.

NEON TUBE PRACTICE. By W. L. Schallreuter. Second edition, revised. New York, Chemical Publishing Company, 1939. 255 pages, illustrated, 9 by 6 inches, cloth, $4.25. The opening section covers in a simplified manner the theory involved; gaseous conduction of electricity, electrodes, vacuum technique, etc. The next section explains tube manufacture, practical uses, and methods of installation. Various causes of failures are subsequently treated, and the final section is devoted to special tubes and discharge lamps, including mercury and sodium vapor lamps.

MODERN MAGNETISM. By L. F. Bates. Cambridge, England, University Press; New York, The Macmillan Company, 1939. 340 pages, diagrams, etc., 9 by 6 inches, cloth, $4.50. Attempts to treat the subject from the experimental rather than the theoretical point of view. Prominence is given to a description of fundamental experiments, and accounts are given of much experimental work, particularly foreign work, of importance to those interested in industrial applications of magnetic materials.

THE MANAGEMENT OF MUNICIPAL PUBLIC WORKS. By D. C. Stone. Chicago, Public Administration Service, 1939. 344 pages, diagrams, etc., 10 by 7 inches, cloth, $3.75. The science of management as developed in industrial plants is here applied to municipal public works administration. Based on actual practice, the material covers all phases of accounting, purchasing, administration, etc., including many illustrations of sample forms. May serve as a reference manual as well as a textbook.

THE JOURNAL OF THE ROYAL TECHNICAL COLLEGE. Volume IV, Part 3, January 1939, pages 421–605. Glasgow, Scotland, Royal Technical College. Illustrated, 10 by 7 inches, paper, 10s. 6d. This publication constitutes a record of some of the research work carried out in the college by the staff and senior students. The topics include investigations in physical chemistry, metallurgy, mechanics, electrical measurements, photo-elasticity, etc.

HOCHFREQUENZTECHNIK. Two volumes. (Lehrbücher der Feinwerktechnik, edited by K. Gehlhoff.) By J. Kammerloher. Leipzig, C. F. Winter'sche Verlagshandlung, 1938–39. Diagrams, etc., 8 by 6 inches. Volume I, 199 pages, paper 6.90 rm., bound, 7.60 rm.; Volume II, 326 pages, paper, 11.50 rm., bound, 12.80 rm. In the first volume the theory and characteristics of electromagnetic oscillatory circuits are developed, covering capacitors and inductance coils in general, various closed and open circuits, losses, and calculation fundamentals. The second volume considers the fundamentals and characteristics of diodes, triodes, and multi-grid electron tubes, amplifiers of varying a-c voltages, and sound-frequency amplifiers, including comparisons of theoretical with experimental values.

ALTERNATING-CURRENT BRIDGE METHODS. By B. Hague. Fourth edition. New York and Chicago, Pitman Publishing Corporation, 1938. 587 pages, diagrams, etc., 9 by 6 inches, cloth, $8.50. This new edition contains theoretical and practical information dealing with a-c bridges for the measurement of inductance, capacitance, and effective resistance at low and telephonic frequencies. The separate chapters cover fundamentals, symbolic theory, apparatus, the classification of bridge networks, and the various available methods, including necessary precautions.

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Transactions

Papers and Discussions Comprising Pages 1–34 of the 1939 Volume

# Application of Capacitance Potential Devices

By J. E. CLEM
FELLOW AIEE

THERE has been evident need for some time for a general review of the factors influencing the application of capacitance potential devices. This need has been accentuated by the increasing use of bushing potential devices and the extension of the field of application made possible by the introduction of the coupling-capacitor potential device.

At the higher system voltages the cost of transformers for supplying potential for relays has been a serious deterrent to the use of the relay equipment otherwise best adapted to the requirements of the installation. The introduction of the bushing potential device, and particularly of the coupling-capacitor potential devices later, offered a more economical method of obtaining the desired potential. The first applications of bushing potential devices were for synchronizing and voltage indication, and later their use was extended to certain types of relaying. The introduction of the coupling-capacitor potential devices extended the field of application by making practical the use of a nonresonant device and by making available higher outputs. These devices made possible a wider application of the use of carrier-current relay schemes, further increasing the field for the potential devices.

Any misunderstanding of the inherent limitations of these devices may result in a failure to recognize their possibilities, or in a tendency to use the device outside its proper field of application. Therefore, this paper has been written to discuss briefly general considerations in regard to types of devices and the selection of the means of obtaining instrument or relay voltage, to review the accuracy considerations and application requirements, to describe the types of devices, and to present an analysis of the network constituting the device.

## General Considerations

### Types of Devices

Capacitance potential devices are divided into two general classifications: resonant and nonresonant. The resonant device may be used with a bushing or a coupling capacitor, the nonresonant should be used only with a coupling capacitor. In general the outputs from coupling-capacitor potential devices are considerably higher than the output from bushing potential devices.

The resonant device may be adjusted so that the output voltage is in phase with the system line-to-ground voltage. With this adjustment the series reactance is approximately equal to the reactance of the auxiliary capacitor, that is, nearly in parallel resonance with it.

No series reactance is used with the nonresonant device and the phase angle between the output voltage and the system line-to-ground voltage may be adjusted over nearly the entire range from 0 to 180 degrees lead, with maximum output at approximately 90 degrees lead.

### Selection of Means of Obtaining Voltage

The choice of the method of obtaining from the circuit voltage a reduced voltage should be governed by the use to which the voltage is to be put. Obviously an ideal device would give a voltage exactly in phase with, and of constant proportionality to, the circuit voltage. However, an ideal device is not available nor is it of practical necessity.

The most accurate means at present is the conventional potential transformer. Its characteristics may be accurately predetermined and they remain practically constant over the usual range of operating conditions. Potential transformers should be used whenever revenue wattmeters are to be operated or when known and consistent accuracy is the controlling factor.

Potential devices may be used when their variation in accuracy is less than that permissible from consideration of the use to which the voltage is to be put. They can be adjusted for a definite accuracy with a definite set of operating conditions but are subject to much greater variation in accuracy from changes in operating conditions. The resonant device ranks next to the potential transformer in performance, with the nonresonant device next.

For example, if only voltage indication and synchronizing are considered, a nonresonant device would be entirely suitable; if distance relaying is considered the resonant device may be used. Each application should be carefully analyzed to make sure that the accuracy requirements are not beyond the performance of the devices before they are specified.

### Available Output Watts "W"

The gross input from a circuit to a capacitance potential device network is given by the following expression, developed in appendix I

$$W = 2\pi f C_1 E E_2 \sin \alpha \tag{10}$$

in which $f$ is the system frequency, $E$ and $E_2$ are, respectively, the line and tap voltage to ground with the angle $\alpha$ between them, and $C_1$ is the coupling capacitance in farads.

The net possible output of the device will be the watts calculated by use of this equation decreased by the losses in the device. The rating of the resonant devices is less than the possible net to insure suitable performance characteristics.

## Accuracy Considerations

As mentioned previously, a potential device is subject to some inaccuracies not present in a potential transformer. It is therefore pertinent to analyze the factors affecting the accuracy to determine the advisable field of application for the devices. The more important

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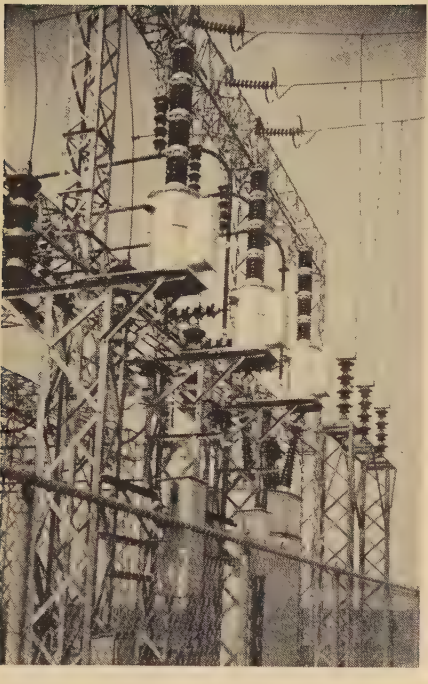


**Figure 1.** Resonant coupling capacitor illustrating unit type of assembly

factors are leakage, changes in burden, line voltage, system frequency, temperature, and transients.

LEAKAGE

Leakage over the surface of the coupling capacitor or over any insulation in the potential tap circuit may cause appreciable error. However, this error can be eliminated by proper design.

Leakage over the coupling capacitors to the primary winding would cause a change in the phase angle of the current drawn from the circuit and introduce an error into the indication of the device. This, however, has been overcome by constructing the potential device, auxiliary capacitor, and coupling capacitor as a unit so that this leakage current goes direct to ground, without the possibility of affecting the accuracy. See figure 1.

Leakage occurring to ground between the coupling-capacitor terminal and the device winding would also introduce error. However, this has also been overcome by the unit assembly of the parts.

The availability of the coupling capacitor stimulates its use also for carrier-frequency coupling. The carrier circuit must have minimum high-frequency leakage, this is also obtained by the unit assembly, and by the use of Performite-insulated cable with each end shielded from the weather, and supported by vertically mounted oversized insulators.

Bushing potential devices are protected from the effects of leakage because the capacitance is completely enclosed and an armored cable is used for the tap lead.

BURDEN CHANGES

With few exceptions the impedances of potential coils of relays and instruments are essentially constant at all voltages so that the only cause for changes in burden is the connection or disconnection of devices such as voltmeters and synchroscope. Usually the error produced from this cause is relatively unimportant because the load change is relatively small. If the load change is enough to cause too great a change in accuracy, a dummy burden can be arranged to exchange positions with the burden being switched so that no resultant change in burden at all will occur.

A closed magnetic circuit in the gross load on the network may introduce an error. Although the capacitor $C_a$, for correcting power factor, may be adjusted to give unity power factor at normal voltage, some difficulty may still arise. For example, reference to the diagrams (figure 10 and figure 5) will show that the auxiliary capacitor $C_2$ is substantially in parallel with the device transformer, the adjustment transformer if used, and with the burden. Under certain conditions this circuit will become unstable and steady overvoltages of a highly distorted wave shape will exist across the transformer, and the relays, etc., which make up the load. This has been overcome in the device network by designing the device and adjustment transformers with low magnetic density and by providing an additional winding in the adjustment unit (see figure 5) so that residual voltage may be obtained without the use of an auxiliary transformer.

Operating engineers should be rather cautious in regard to the use of relays which require the use of auxiliary transformer, so as to avoid the possibility that this trouble may be set up by causes external to the device.

This difficulty has not been encountered with bushing potential devices, probably because of their more limited sphere of application and because the value of the auxiliary capacitance is much lower.

CHANGE IN SYSTEM VOLTAGE

Protective relays are called upon to act at the time of a fault and at this instant the line voltage is usually low. Since the magnetizing current is an appreciable portion of the total load taken by the network, the impedance of the network changes appreciably, and with it the accuracy. The performance of the device should be investigated at the critical fault condition and, if necessary, readjusted to give the desired performance under these conditions.

Ordinary fluctuations in system voltage do not have an appreciable effect on the accuracy of the potential devices.

CHANGE IN FREQUENCY

Variations in frequency affect the accuracy of the devices by changing the relative values of the inductive and capacitive impedances in the network. The effect depends to some extent upon the voltage of the circuit and the burden being carried by the device. The following tabulation gives the approximate variation in accuracy for a 115-kv circuit with the device adjusted for an output of $(50 + j15)$ volt-amperes.

| Cycles | R C F | Angle |
|---|---|---|
| 58 | 1.021 | +1.52 |
| 60 | 1.000 | +0.02 |
| 62 | 1.088 | —2.65 |

Under steady-state conditions this effect is ordinarily of no consequence because present-day systems operate at a very steady and constant frequency. Under fault conditions the device will usually have performed its function before the frequency has changed appreciably.

CHANGES IN TEMPERATURE

Changes in temperature affect the capacitance slightly and cause a slight error in the nonresonant device. If the dielectric in the auxiliary capacitor is different from that in the coupling capacitors a slight error will be caused in the accuracy of the resonant device. For the new oil-filled paper-dielectric coupling capacitor and accompanying auxiliary capacitors, the capacitance variation from −40 degrees to +100 degrees centigrade is approximately 3.5 per cent.

Changes in temperature affect the burden and affect directly the accuracy of the nonresonant device as can be seen from the characteristics. The affect on the accuracy of the resonant device is negligible, as can also be seen from the characteristics. Usually the burdens are installed where the temperature changes are not extreme so that the temperature effect is not a serious factor.

TRANSIENTS

Potential devices, consisting of a network of capacitances and inductances, are inherently subject to transient disturbances occurring when system conditions change suddenly, as when a circuit is switched on.

Figures 2*a* and 2*b* are representative of what may occur on switching in. In figure 2*a* trace 1 shows the residual voltage from the potential devices and trace 2 shows the residual current. The oscillatory character of the residual voltage in connection with the large unidirectional component in the residual current gives incorrect information to the directional ground relay and the circuit may be dropped out unnecessarily. In figure 2*b* there is a marked oscillation in the residual current instead of a large unidirectional component. In this case incorrect information will also be given to the directional ground relay and the circuit may drop out.

It should be noted that it requires an error in the current indication as well as in the potential device indication to cause an incorrect operation of the relay.

The incorrect operation of the directional ground relay caused by the inherent transient characteristics of the potential device in combination with the transient error in the current indication have been overcome and successful operation secured by giving the overcurrent relay a sense of discrimination that enables it to distinguish between the true ground fault condition and a switching transient.

Power systems are subject to overvoltages of a semi-steady character and of a transient nature. The first type occurs when a circuit is disconnected at the load end, in which case the voltage will build up to a value seldom exceeding 1.75 times normal when voltage regulators are used. The devices must withstand this overvoltage without becoming unstable and the design has been made accordingly.

The second type occurs from switching. Records show that switching surges above three times normal are of very short duration, and that few even exceed one-quarter of a 60-cycle period. Accordingly the devices are not required to withstand steady voltages in excess of two times normal, but they must withstand transient voltages without becoming unstable. The devices have been designed to remain stable when subjected to long-wave switching surges of three times normal. Sustained transient overvoltages (arcing grounds) in excess of the relief gap setting may cause damage to the gap electrodes from continuous arcing.

## Application Requirements

### Synchronizing

The requirements for synchronizing are relatively simple—reasonably good phase angle and voltage indication. Since the nonresonant device may be adjusted over a wide range of phase angle it is well suited for use in synchronizing. The voltage indication to the synchroscope need not be precise so that again the nonresonant device is entirely suitable.

### Voltage Indication

The accuracy requirement for ordinary switchboard indication of voltage is well within the range of potential devices.

### Metering

Resonant potential devices may be used for metering in those cases when a reasonably accurate indication of load or kilowatt-hours is wanted. When revenue metering is considered conventional potential transformers should be used.

### Relaying

The various types of relays commonly used for protection on electrical systems require varying degrees of accuracy of the potential supplied to them. The ordinary directional relay characteristics are such that almost any reasonably good replica of the line potential will be suitable. A shift of several degrees in phase angle or of several per cent in ratio would have no noticeable effect upon the overall operation of the relay system.

On the other hand, high-speed relays of the distance type require an accurate reproduction of the primary voltage or, lacking this, an accurate knowledge of the variation. With the high-speed distance relays the speed of response is great enough that any transient in the voltage supply due to a sudden change in the primary voltage must be investigated to see that there is no shift in phase angle which might cause incorrect operation. If there is simply a time delay transient, the speed of response of the relay system will be somewhat affected, but this, in general, is not serious as compared to a large phase-angle shift during a transient period.

High-speed protection of the carrier pilot type works fundamentally upon the indication of directional relays, and if there be no transient phase-angle shift of large extent, the question of accuracy or fixed error is not of any importance with this type of protection.

It is of more importance to the relay engineer to know the errors of the device than that any attempt should be made to build something capable of supplying a potential having no ratio or phase-angle error. In general, if the variations are known, it is possible to make the requisite relay settings to compensate for them. It should be pointed out that it is really more important that any errors which may exist in either the ratio or phase-angle relation between secondary voltage and the primary voltage be

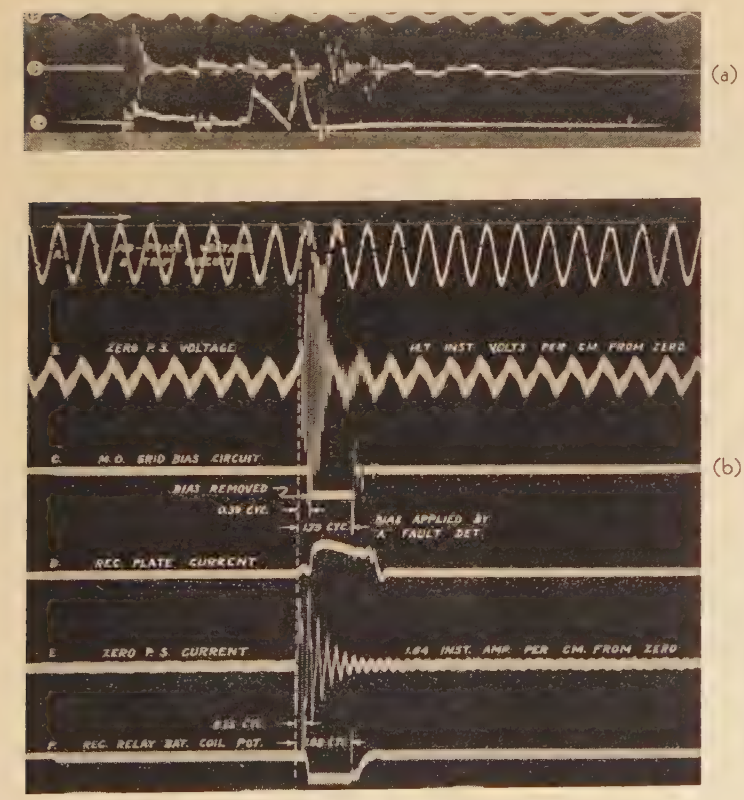


Figure 2. Switching-in transients

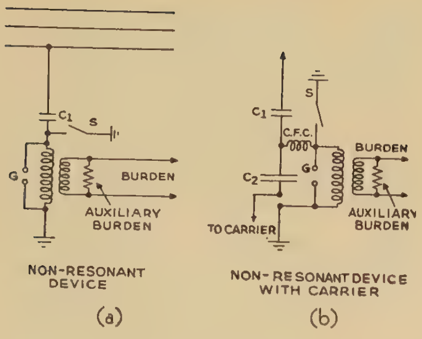


**Figure 3.** Nonresonant potential device

constant, because if these errors change, then it may be difficult or impossible to obtain the desired operation of the relay system.

It is, therefore, evident in the application of capacitor potential devices to a protective relay system that no hard and fast rule can be laid down as to whether they are suitable or not, but it is a very simple matter to make this decision from the known characteristics of the potential supply and the requirements of the relays.

The types of relays which may commonly be supplied from potential devices are:

Phase directional relays
Balanced current relay restraint coils
Ground current directional relays
Carrier pilot directional relays
Distance relays
    Impedance
    Reactance

These relays have been tabulated in approximately the order of severity of requirements.

A phase-fault directional relay merely has to make a comparison of the angle between current and voltage and determine whether the fault power flow is in one direction or the other. Since the two conditions are 180 degrees apart, and since the relays are customarily arranged to have maximum torque in the middle of the possible angular range of short-circuit currents, an error of even 20 degrees makes only a small change in torque and would never cause a false indication. The ratio error is also of small consequence as it also merely changes the torque slightly. Hence this type of relay will tolerate large errors in the potential device without any adverse effect upon its performance. It is probably safe to say that an error of 20 degrees to 30 degrees and 20 per cent to 30 per cent in the potential device under low-voltage conditions, would be unnoticeable in the action of phase directional relays during short circuits.

One type of high-speed balanced current relay is provided with potential restraining coils in order to facilitate switching operation rather than to provide any real change in the relay characteristic under fault conditions. The requirements are not at all stringent so that ratio errors as high as 30 per cent at low voltage are entirely acceptable. At normal voltage the errors should be kept below 15 per cent if the load over one circuit ever approaches the setting of the relay, while a higher error is permissible where the secondary current never reaches the minimum operating values. Phase angle error is of no consequence whatever during faults but at normal voltage should be kept below 15 degrees where the circuit is heavily loaded and the power factor leading.

The operating torque and hence the time of a directional ground current relay, is a function of the product of the zero-sequence current, the zero-sequence voltage, and some function of the angle between them. In many of these relays the operating torque opposes a resetting spring that provides definite values of minimum operating watts. The requirements are therefore a little more exacting than in the case of the phase relays because actual values of current and voltage are involved in the operation of the relay. On the other hand, there are so many unknown and variable factors in the zero-sequence current path that are not susceptible to exact determination, that there is little necessity of requiring great accuracy in the potential device. The final settings of ground current relays are usually determined by experience so that errors in the potential supply are not very significant. If the error is within 15 degrees and 15 per cent, potential devices should be satisfactory sources of voltage for directional ground current relays.

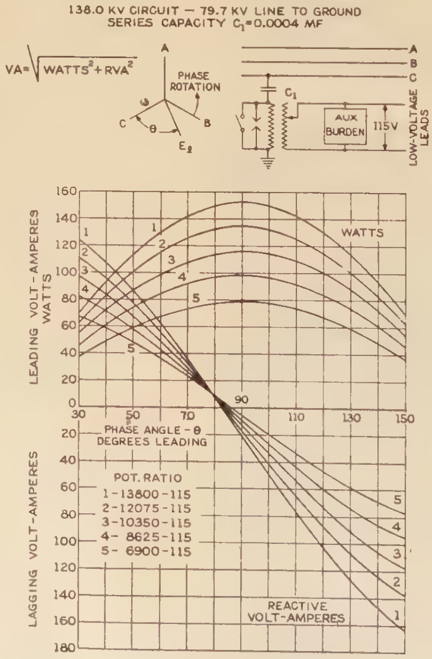


**Figure 4.** Typical characteristic curves of nonresonant potential device

On carrier pilot relaying the discrimination is obtained by means of phase and ground current directional relays and hence the requirements are quite similar to those enumerated for these types of relays. A somewhat greater accuracy is desirable because the results of relay actions at the two ends are compared via carrier. This is particularly true of a system subject to power oscillations during which the relay must surely block any tripping. Throughout a power swing the current, voltage, and angle between them are constantly changing and are different at any instant at different points in the system.

It is important that the direction of power flow appear to the relays to be in the same direction as it actually is on the line. Otherwise during the changing conditions the relay at one terminal of the line may indicate a reversal of power flow before such reversal actually occurs. The ratio error is of relatively small importance, but the angular error should be held to very close limits if this end is to be achieved. On the other hand, the design of the relay equipment at the present time is such that a 10-degree error would probably not noticeably affect the overall operation and may, therefore, be tolerated.

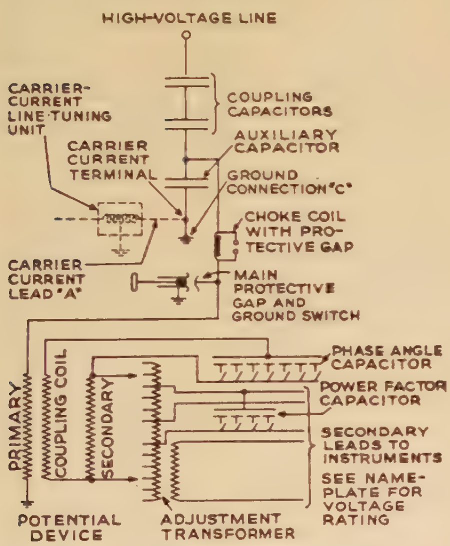
Distance relays are, in effect, triangulating instruments like a surveyor transit. Any error in the base quantities supplied to them has a direct, and usually linear, effect upon the accuracy of their performance. In a true impedance relay the error in distance measurement is a direct function of the ratio error but angular error would not influence it. Actually the phase relation of the current and voltage does have an appreciable effect upon most impedance relays but in a well designed device it may be made small.

Reactance relays depend upon angular relationships as well as magnitude comparisons but because of the trigonometric function involved, the error in distance measurement resulting from angular errors of current and potential devices, is not a fixed quantity. Upon lines having a high reactance-to-resistance ratio a few degrees error is inconsequential as the distance measured is a function of the sine of an angle near 90 degrees. On the other hand the sine of smaller angles, such as 40 degrees, changes much more rapidly per degree error. Striking an average, it is suggested that the ratio error should be less than five per cent for any distance relay application, when the primary voltage is approximately the value to be expected for a fault at the end of the instantaneous zone, and that the angular error should be below five degrees for reactance relays and 15 degrees for impedance relays under the same voltage conditions.

## Types of Devices

### COUPLING-CAPACITANCE POTENTIAL DEVICES

*Nonresonant Device.* This is the simplest type of capacitance potential device and consists essentially of a transformer in series with a capacitance as shown in figure 3*a*. The essential features of this device are that the voltage may be adjusted to any desired phase angle, practically from about 30 degrees to 150 degrees, in relation to the line-to-ground voltage, and that once the adjustment is made the total burden must remain constant. This requires the use of an auxiliary burden which must be changed when the useful burden is changed. Typical characteristic curves are shown in figure 4 applying to the devices used with the porcelain-type coupling capacitors. Similar curves apply to nonresonant devices used with the new oil-filled paper-dielectric coupling capacitor except that the output is higher.



FOR POTENTIAL DEVICE OPERATION ONLY–CARRIER-CURRENT TERMINAL IS DIRECTLY GROUNDED AT GROUND CONNECTION "C"

FOR BOTH POTENTIAL DEVICE AND CARRIER-CURRENT COUPLING–REMOVE GROUND CONNECTION "C" AND CONNECT CARRIER-CURRENT TERMINAL TO CARRIER-CURRENT LINE TUNING UNIT WITH LEAD "A"

**Figure 5. Resonant coupling-capacitor potential device**

*Resonant Device.* The resonant potential device, when used within its inherent limitation, provides an economical and reliable means of obtaining potential for use with indicating and recording instruments and for relaying purposes. Figure 5 represents the connection for obtaining line-to-ground voltage from one conductor. To obtain phase voltages two or three coupling-capacitor assemblies and potential devices would be required. Characteristic curves are shown in figure 6.

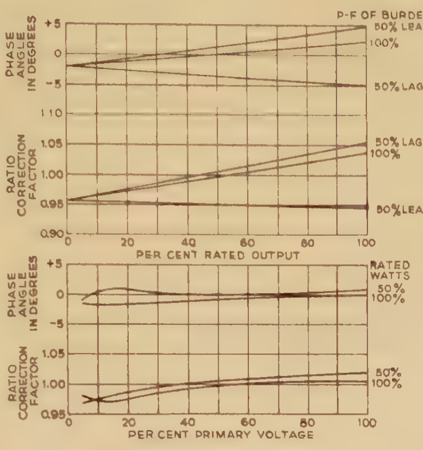


**Figure 6. Typical characteristic curves of resonant potential devices**

The design of the capacitance potential devices is such that adjustments of voltage and phase angle may be made in steps of one per cent for voltage and one degree for phase angle. These adjustments are made by means of an adjustment unit which consists of an autotransformer giving 69/115 wye volts and 115 volts delta, together with a block of capacitors for phase-angle adjustment, and another block of capacitors for adjusting the net power factor of the burden to unity. Voltage control is by means of taps on the primary side of the autotransformer.

*Simultaneous Device and Carrier Coupling.* Simultaneous use with carrier of either the resonant or nonresonant device with coupling capacitors requires the addition of a carrier-frequency choke to prevent dissipation of the carrier signal in the potential device. It is essential that this choke be very carefully designed so that it has a very high impedance over the carrier-frequency range and at the same time it must have very low losses. It must be able to withstand the lightning surges which are transmitted to it through the coupling capacitors, and it must also stand the high-potential test of the potential device.

When it is desired to use carrier in conjunction with the nonresonant potential device an auxiliary capacitor as well as a carrier-frequency choke must be added to the network as indicated in figure 3*b*. The addition of the auxiliary capacitance necessitates the addition of a compensating inductance (not shown) to balance out the capacitive volt-amperes drawn by the auxiliary capacitance.

### BUSHING POTENTIAL DEVICES

*Resonant Device.* These are, in general, of the same design as those used with coupling capacitors. Taps in the transformer itself take the place of the adjustment transformer. Simultaneous carrier operation is impractical because the capacitances are built into the bushing in such a way that the auxiliary capacitance, tap to ground, cannot be isolated from ground for the carrier connection.

Characteristic curves are shown in figure 6.

## Appendix I

### Available Output

The available output from a capacitance potential device is the total input to the network decreased by the losses in it. The gross input to the network can easily be determined. In figure 7*a*, $E_l$ represents the net load, or burden voltage (see list of symbols and terms at end of appendix IV), and is drawn in figure 7*b* as the reference vector. Now draw in the net load current $I$ at its angle of lag behind the net load voltage $E_l$.

Then in figure 7*b* add the voltage drop $E_{dx}$ to the load voltage $E_l$ and obtain the tap voltage $E_2$, from which is obtained the exciting current $I_m$ and the current $I_2$

$$E_2 = E_l + IZ_{dx} \tag{1}$$

$$I_m = \frac{E_2}{Z_m} \tag{2}$$

$$I_2 = \frac{E_2}{Z_2} \tag{3}$$

Now find $I_1$, the current in the coupling capacitor as the sum of the load current, the exciting current, and the current in the auxiliary capacitor.

$$I_1 = I_l + I_m + I_2 \tag{4}$$

From the current $I_1$ and the impedance $Z_1$ of the coupling capacitor find the voltage drop across the coupling capacitor, $E_1$, and locate it in figure 7*b*. It is

$$E_1 = I_1Z_1 \tag{5}$$

Now add $E_2$ to $E_1$ and get $E$ as

$$E = E_1 + E_2 \tag{6}$$

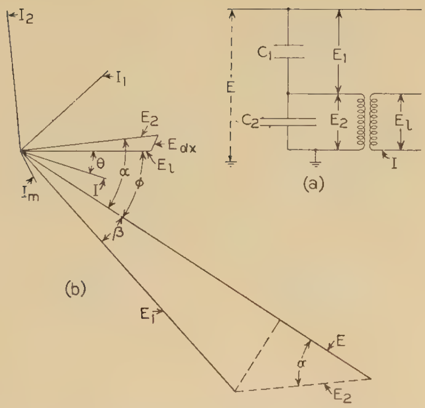


**Figure 7. General equivalent circuit and vector diagram of potential device**

From figure 7*b* it is easy to see that the power taken from the line is

$$W = EI_1 \sin\beta \tag{7}$$

But

$$I_1 = \frac{E_1}{Z_1} \tag{5}$$

So that

$$W = \frac{EE_1}{Z_1}\sin\beta \tag{8}$$

But from the figure

$$E_1 \sin\beta = E_2 \sin\alpha \tag{9}$$

So that (8) becomes

$$W = 2\pi f C_1 EE_2 \sin\alpha \tag{10}$$

Equation 10 may be used to determine the maximum watts that may be taken from the circuit. The watts available at the load voltage $E_l$ will be the quantity calculated from equation 10 decreased by the losses in the network.

## Appendix II

### Analysis of Network Circuit

*Case 1—Figure 8—Series Reactor in High-Voltage Side of Transformer.* As mentioned in appendix I the load current $I$ is net, that is the current in the output winding of the transformer. The lagging component of the burden current is neutralized by the current in the power factor corrective capacitor $C_a$. Then

$$E_l = IZ_l \tag{11}$$

and the voltage $E_t$ on the input side of the transformer is the load voltage plus the drop through the transformer,

$$E_t = E_l + IZ_d = I(Z_l + Z_d) \tag{12}$$

The exciting current is

$$I_m = \frac{E_t}{Z_m} \tag{2b}$$

and this added to the load current gives the current which flows through the reactor, and the drop across the reactor.

$$I_x = I + I_m = I\left(1 + \frac{Z_l + Z_d}{Z_m}\right) \tag{13a}$$

and

$$E_x = I_x Z_x \tag{13b}$$

The tap voltage $E_2$ is the input voltage $E_t$ plus the drop across the series reactor $E_x$.

$$\begin{aligned} E_2 = E_t + E_x &= I(Z_l + Z_d) + I_x Z_x \\ &= I\left(Z_l + Z_d + Z_x + \frac{Z_l + Z_d}{Z_m} Z_x\right) \\ &= IZ_s \end{aligned} \tag{14}$$

and obviously

$$Z_s = Z_l + Z_d + Z_x + \frac{Z_l + Z_d}{Z_m} Z_x \tag{15}$$

Also, the current in the auxiliary capacitor

$$I_2 = \frac{E_2}{Z_2} \tag{3}$$

to which is added $I_x$ to get the current $I_1$ in the coupling capacitor,

$$I_1 = I_x + I_2 = I\left(1 + \frac{Z_l + Z_d}{Z_m} + \frac{Z_s}{Z_2}\right) \tag{16}$$

The voltage drop across the coupling capacitor is $I_1 Z_1 = E_1$ and the line-to-ground voltage is given by

$$\begin{aligned} E &= E_1 + E_2 \\ &= I\left(Z_s + Z_1 + \frac{Z_l + Z_d}{Z_m} Z_1 + Z_s \frac{Z_1}{Z_2}\right) \end{aligned} \tag{6}$$

$$E = I\left(Z_1 + AZ_s + \frac{Z_l + Z_d}{Z_m} Z_1\right) \tag{17}$$

In (17) $A$ is defined as

$$A = \frac{Z_1 + Z_2}{Z_2} \tag{18}$$

Now re-insert the value of $Z_s$ from (15), divide by $A$, rearrange, and obtain

$$\frac{E}{A} = I\left[\frac{Z_1}{A} + (Z_l + Z_d)\left(1 + \frac{Z_1}{AZ_m}\right) + \frac{Z_l + Z_d}{Z_m} Z_x + Z_x\right] \tag{19}$$

$$\text{Let } K = 1 + \frac{Z_1}{AZ_m} \tag{20}$$

and then substitute $K$ in (19), rearrange, and divide by $K$ and get

$$\frac{E}{AK} = I\left[\frac{Z_1}{AK} + (Z_l + Z_d) \times \left(1 + \frac{Z_x}{KZ_m}\right) + \frac{Z_x}{K}\right] \tag{21}$$

$$\text{Let } B = 1 + \frac{Z_x}{KZ_m} \tag{22}$$

and substitute $B$ in (21) and obtain, after rearranging and dividing by $B$

$$\frac{E}{AKB} = I\left(Z_l + Z_d + \frac{Z_1}{AKB} + \frac{Z_x}{KB}\right) \tag{23}$$

$$= I(Z_l + Z_n) \tag{24}$$

In this equation $(Z_n + Z_l)$ is the impedance of the network plus the load when viewed from the capacitance tap and $Z_n$ is defined as

$$Z_n = Z_d + \frac{Z_1}{AKB} + \frac{Z_x}{KB} \tag{25}$$

From (24), (11), (12), (13*b*), the following are obtained

$$\text{Load current } I = \frac{E}{AKB}\,\frac{1}{Z_l + Z_n} \tag{26}$$

$$\text{Load voltage } E_l = \frac{E}{AKB}\,\frac{Z_l}{Z_l + Z_n} \tag{27}$$

$$E_t = \frac{E}{AKB}\,\frac{Z_l + Z_d}{Z_l + Z_n} \tag{28}$$

$$E_x = \frac{E}{AKB}\,\frac{Z_x}{Z_l + Z_n}\left(1 + \frac{Z_l + Z_d}{Z_m}\right) \tag{29}$$

The volt-ampere output of the device is the product of the load voltage and the load current, both net values.

$$VA = E_l I \tag{30}$$

and

$$VA = \frac{E_l^2}{Z_l} \tag{31}$$

From (26),

$$\frac{1}{Z_l} = \frac{\dfrac{E}{E_l\,AKB} - 1}{Z_n} \tag{32}$$

and then

$$VA = \frac{EE_l}{AKB}\,\frac{1 - \dfrac{E_l}{E/AKB}}{Z_n} \tag{33}$$

The expressions for the volt-amperes output can be put into a different form as follows. Let

$$\frac{1}{K} = m\epsilon^{jk} \tag{34}$$

and write $E$ as $E\epsilon^{j\phi}$ in which $\phi$ is the angle from $E_l$ to $E$, and $\epsilon^{j\phi}$ is the factor which expresses the vector phase position of the voltage $E$ in relation to the voltage $E_l$.

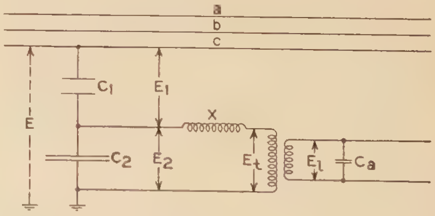


**Figure 8. Potential device with phase angle reactor in high-voltage side of transformer**

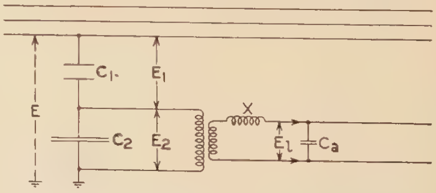


**Figure 9. Potential device with phase angle reactor in low-voltage side of transformer**

xcept when written in this manner $E$ is a vector. When these values are inserted in (33) there results

$$VA = \frac{mEE_l}{AB} \frac{\epsilon^{j(k+\phi)} - \dfrac{E_l}{mE/AB}}{Z_n} \tag{35}$$

It can be shown that the quantity $Z_1/AK$ is the same as $Z_1$, $Z_2$, and $Z_m$ in parallel, and knowledge of this results in the saving of a vast amount of labor if any calculations are made. The proof will be given in two steps to simplify it. First

$$\frac{Z_1}{A} = \frac{Z_1Z_2}{Z_1 + Z_2} \tag{36}$$

which obviously is the impedance of $Z_1$ and $Z_2$ in parallel. Then

$$\frac{Z_1}{AK} = \frac{Z_1}{A} \frac{1}{1 + \dfrac{Z_1}{AZ_m}} \tag{37a}$$

from which

$$\frac{Z_1}{AK} = \frac{Z_1/A \,.\, Z_m}{Z_m + Z_1/A} \tag{37b}$$

which obviously is the impedance of $Z_1/A$ and $Z_m$ in parallel. Therefore $Z_1/AK$ may be written

$$\frac{Z_1}{AK} = \frac{1}{1/Z_1 + 1/Z_2 + 1/Z_m} \tag{38}$$

The equations for the case with the series reactor in the high-voltage side of the transformer can be used as the general case and all others derived therefrom.

*Case 2—Figure 9—Series Reactor in Low-Voltage Side of Transformer; Case 3—Figure 10—Series Reactance Inherent in Transformer.* For these two arrangements the factor $B$ becomes unity and the series reactance, whether inherent in the transformer, or in the low-voltage side, may be dealt with as one term except for one reservation. If the reactor is external to the transformer the drop across it may be calculated separately from the drop in the transformer itself.

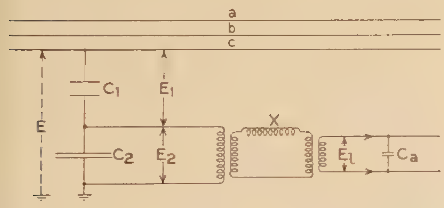


**Figure 10.** Potential device with phase angle reactance inherent in transformer

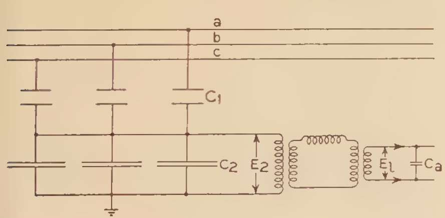


**Figure 11.** One potential device and three coupling-capacitor assemblies used for obtaining zero-sequence voltage

The equations are

$$Z_n = \frac{Z_1}{AK} + Z_d + Z_x \tag{38a}$$

or

$$Z_n = \frac{Z_1}{AK} + Z_{dx} \tag{38b}$$

$$E_l = \frac{E}{AK} \frac{Z_l}{Z_l + Z_n} \tag{39}$$

$$E_2 = \frac{E}{AK} \frac{Z_l + Z_{dx}}{Z_l + Z_n} \tag{40}$$

$$E_x = \frac{E}{AK} \frac{Z_x}{Z_l + Z_n} \tag{41}$$

$$VA = \frac{mEE_l}{A} \frac{\epsilon^{j(k+\phi)} - \dfrac{E_l}{mE/A}}{Z_n} \tag{42}$$

## Appendix III

*Case 4—Figure 11—Zero-Sequence Voltage. One Transformer and Three Capacitors.* This connection is used to obtain zero-sequence voltage. The load voltage

$$E_l = IZ_l \tag{11}$$

and the tap voltage

$$E_2 = I(Z_l + Z_{dx}) \tag{43}$$

from which the exciting current

$$I_m = \frac{E_2}{Z_m} \tag{44a}$$

$$I_m = I \frac{Z_l + Z_{dx}}{Z_m} \tag{44b}$$

and the current in the auxiliary capacitors

$$I_2 = \frac{E_2}{Z_2} \tag{3}$$

$$I_2 = I \frac{Z_l + Z_{dx}}{Z_2} \tag{45}$$

The current in the coupling capacitors

$$I_1 = I + I_m + 3 \tag{46}$$

$$I_1 = I\left[1 + (Z_l + Z_{dx})\left(\frac{1}{Z_m} + \frac{3}{Z_2}\right)\right] \tag{47}$$

Assume that the current $I_1$ divides among the three coupling capacitors in the proportions $a$, $b$, and $c$ so that $a + b + c = 1$, and then

$$\left.\begin{aligned} E_a &= I(Z_l + Z_{dx}) + \\ &\quad aI\left[Z_1+(Z_l+Z_{dx})\left(\frac{Z_1}{Z_m}+\frac{3Z_1}{Z_2}\right)\right] \\ E_b &= I(Z_l + Z_{dx}) + \\ &\quad bI\left[Z_1+(Z_l+Z_{dx})\left(\frac{Z_1}{Z_m}+\frac{3Z_1}{Z_2}\right)\right] \\ E_c &= I(Z_l + Z_{dx}) + \\ &\quad cI\left[Z_1+(Z_l+Z_{dx})\left(\frac{Z_1}{Z_m}+\frac{3Z_1}{Z_2}\right)\right] \end{aligned}\right\} \tag{48}$$

in which $E_a$, $E_b$, and $E_c$ are system voltages line to ground. Let

$$Z_n = \frac{Z_1}{3AK} + Z_{dx} \tag{49}$$

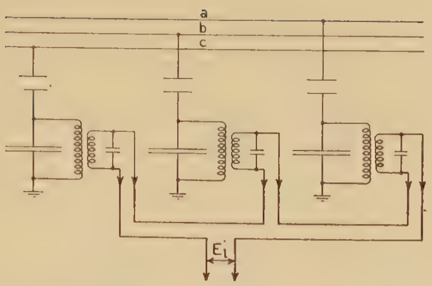


**Figure 12.** Three potential devices and three coupling-capacitor assemblies used for obtaining zero-sequence voltage

and then the solution of these equations is

$$E_l = \frac{E_o}{AK} \frac{Z_l}{Z_l + Z_n} \tag{50}$$

$$E_2 = \frac{E_o}{AK} \frac{Z_l + Z_{dx}}{Z_l + Z_n} \tag{51}$$

$$VA = \frac{mE_oE_l}{A} \frac{\epsilon^{j(k+\phi)} - \dfrac{E_l}{mE/A}}{Z_n} \tag{52}$$

Note that in these equations $K$ is different because the network is different in detail.

## Appendix IV

*Case 5—Figure 12—Zero-Sequence Voltage; Three Transformers; Three Coupling Capacitors.* Rearrange (39) and get

$$\frac{E}{AK} = E_l + IZ_n \tag{53}$$

Write $E_p$ for $E/AK$ and $E_s$ for the secondary (low) voltage of the transformers, and then for the phases $a$, $b$, and $c$, respectively

$$\begin{aligned} E_{ap} &= E_{as} + IZ_{an} \\ E_{bp} &= E_{bs} + IZ_{bn} \\ E_{cp} &= E_{cs} + IZ_{cn} \end{aligned} \tag{54}$$

Add and write

$$E_{op} = \frac{E_{ap} + E_{bp} + E_{cp}}{3} \tag{55}$$

$$E_l = E_{as} + E_{bs} + E_{cs} \tag{56}$$

$$Z_{on} = \frac{Z_{an} + Z_{bn} + Z_{cn}}{3} \tag{57}$$

$$I = \frac{E_l}{Z_l} \tag{11}$$

and then

$$E_l = E_{op} \frac{3Z_l}{Z_l + 3Z_{on}} \tag{58}$$

$$E_{as} = E_{ap} - E_{op} \frac{3Z_{an}}{Z_l + 3Z_{on}} \tag{59}$$

The other phase voltages as well as the voltage drop across the series reactance can be determined in a similar manner.

It should be noted that in this case the power factor correction capacitor $C_a$ is not included in the load and, therefore, must be included in $Z_n$ for each transformer.

### List of Symbols

$W$ = Watts taken from the circuit

$VA$ = Load volt-amperes

$E$ = Circuit voltage—line to ground

$E_l$ = Load or burden voltage

$E_d$ = Voltage drop in transformer impedance

$E_x$ = Voltage drop across series impedance

$E_{dx}$ = Voltage drop of combined transformer and series impedance either when latter is inherent in transformer, or in output side

$E_2$ = Tap voltage, or voltage across high-voltage side of transformer when auxiliary capacitance is not used

$E_1$ = Voltage across coupling capacitors

$E_t$ = Voltage on input side of transformers, used when series reactor is on high-voltage (input) side of transformer

$E_a, E_b, E_c$ = Respective phase voltages to ground

$E_x$ = Pseudo primary voltage of transformers = $E/AK$

$E$ = Secondary voltage of transformer

$I$ = Load current — burden plus compensator, i.e., net

$I_m$ = Exciting current of transformer

$I_2$ = Current in auxiliary capacitor

$I_1$ = Current in coupling capacitor

$I_x$ = Current in series reactor when it is on the high-voltage (input) side of transformer

$Z_l$ = Impedance of load-burden plus compensation, i.e., net

$Z_d$ = Impedance of transformer windings

$Z_x$ = Impedance of series inductance

$Z_{dx}$ = Combined impedance of transformer and series inductance either when latter is inherent in the transformer, or in the output side

$Z_m$ = Exciting impedance of transformer

$Z_1$ = Impedance of coupling capacitor

$Z_2$ = Impedance of auxiliary capacitor

$Z_n$ = Impedance of network when viewed from the potential tap

$Z_{12}, Z_{23}, Z_{31}$ = Phase impedances of delta-connected burden

$\theta$ = Angle between the net load voltage $E_l$ and net load current $I$

$\phi$ = Angle between net load voltage and the circuit line-to-ground voltage

$\alpha$ = Angle between $E_2$ and $E$

$\beta$ = Angle between $E$ and $E_1$

$k$ = Angle associated with $1/K$

$C_1$ = Coupling capacitor

$C_2$ = Auxiliary capacitor

$C_a$ = Power factor corrective capacitor

$A = \dfrac{Z_1 + Z_2}{Z_2}$ = Reciprocal of the ratio of the tap voltage to the circuit line-to-ground voltage at no load

$B = 1 + \dfrac{Z_x}{KZ_m}$

$K = 1 + \dfrac{Z_1}{AZ_m}$ one transformer, and one coupling capacitor

$$\frac{Z_1}{AK} = \frac{1}{1/Z_1 + 1/Z_2 + 1/Z_m}$$

$K = 1 + \dfrac{Z_1}{3AZ_m}$ one transformer, and three coupling capacitors

$$\frac{Z_1}{3AK} = \frac{1}{3/Z_1 + 3/Z_2 + 1/Z_m}$$

$$\frac{1}{K} = m\epsilon^{jk}$$

$a, b, c$ = Used as subscripts to indicate the respective phases

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## Discussion

**L. F. Kennedy** (General Electric Company, Philadelphia, Pa.): The use of capacitance potential devices for relaying purposes has not been very great because most engineers were inclined to question their accuracy. Mr. Clem has covered the factors affecting accuracy and at the same time given the accuracy requirements for different classes of service. The knowledge of what affects the accuracy and the broad requirements given should certainly be helpful in determining when and where these devices may be used.

In connection with the application requirements, it should be borne in mind that the figures of accuracy given in the paper are naturally those applying to the general case of application of the specific relay involved. There will be limiting cases with the different types of relaying wherein greater accuracy than that specified in the paper will be necessary. I feel it is sufficient merely to call attention to this fact and that all of us will be able to recognize those cases requiring greater accuracy when they arise.

The causes of errors in the potential device are in at least two cases of particular interest to the relay engineer. First, Mr. Clem points out that the use of a closed magnetic circuit in the gross load may introduce an error and even a type of oscillation under certain conditions. Some relay devices of necessity contain closed magnetic circuits, but it seems that the difficulty pointed to by Mr. Clem can be avoided even though these closed magnetic circuits are used, provided their volt-ampere characteristic is linear over the operating range. As an example of this, a recent case showed that oscillation was caused by the use of a wye/delta auxiliary transformer for obtaining zero-sequence voltage. The originally installed transformer had the saturation curve shown by $A$ on figure 1 of this discussion. The substitution of a different auxiliary transformer which did not saturate until a much higher voltage was impressed, as indicated by $B$, eliminated the tendency to oscillation. I should like to have Mr. Clem specifically say whether any trouble is liable to be encountered with a linear burden. If a linear burden does avoid these troubles, then the burden under all conditions is the important factor rather than the presence of a closed magnetic circuit.

Mr. Clem has pointed out that incorrect relay operation has resulted because of the transients which are inherent in these potential devices. Since these incorrect operations were caused by a combination of transients produced by potential devices and also by transients in the current circuit, the means adopted to prevent incorrect operation actually were applied to current relays in the equipment. To prevent operation on the type of transient shown in figure 2*a*, wherein there is a relatively low-frequency current present caused by the decay of the d-c transient, a high-speed induction-type relay was used which would not respond to this low frequency but would operate in approximately one cycle of normal system frequency. In the second case, figure 2*b*, in an application involving a magnetic type of relay, incorrect operation was avoided by means of a by-pass shunt in parallel with the relay coil providing a path for the high-frequency current.

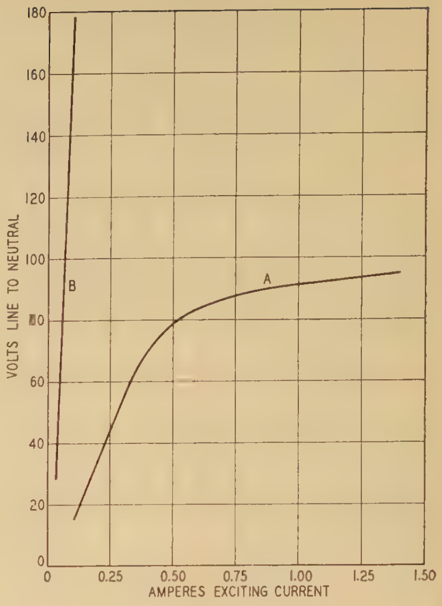

Figure 1

Mr. Clem has pointed out that the potential supply from the capacitance devices has certain transients not encountered with potential transformers. It is possible theoretically to analyze the expected performance of relays from a supply of this kind. It appears safe to say that the transients which are present will not cause any incorrect operations. They may result in slightly slowing up some of the higher speed types but that appears to be all. There is, however, a great lack of any conclusive field results to verify these theoretical conclusions. It would seem to be in order to have a review made of the operating experience with various types of relays used in conjunction with potential devices in order that their application could be put on the firm basis which always comes from field verification of theoretical considerations.

**J. W. Farr** (General Electric Company, Pittsfield, Mass.): The more important causes for potential device inaccuracies such as leakage, changes in burden, system voltage, frequency, and temperature, and transients have been briefly discussed in Mr. Clem's paper.

The amount of error resulting from these causes is mostly dependent on the design and circuit arrangement of the potential device.

The following discussion of Mr. Clem's paper applies particularly to ratio and phase-angle errors in a resonant-circuit device when caused by changes in burden and system voltage.

The resonant potential device consists essentially of a voltage transformer for stepping down the tap voltage $E_2$ to a suitable value for operating relays, instruments, etc., and series inductive reactance $Z_x$ or $Z_{dx}$ for adjusting the over-all circuit reactance to approximately zero, so that the phase angle will be substantially zero and the circuit will have a minimum amount of regulation. The series reactance may be obtained by connecting a suitable reactor in series with either the primary or secondary side of the transformer or it may be obtained as an inherent characteristic of the transformer itself.

Therefore, in general, three methods or arrangements may be used in designing the resonant-circuit device. These will be referred to as follows:

Case *A*—Voltage transformer with series reactor in the primary or high-voltage side.

Case *B*—Voltage transformer with series reactor in the secondary or low-voltage side.

Case *C*—Voltage transformer with inherent reactance characteristics.

The following comparisons are made to indicate which of these circuit arrangements should be most satisfactory from the standpoint of both operating characteristics and economy of construction.

Case *A* and *B* each use a separate transformer for stepping down the voltage and a reactor to provide the required inductive reactance. Taps are contained in both the transformer and the reactor for making adjustments.

However, cases *A* and *B*, differ in that the reactor is placed in the primary circuit and secondary circuit of the transformer, respectively. The reactor in case *A* must be designed to stand the primary circuit voltages and consequently results in a much larger and more costly device. However, this design has higher accuracy and burden rating for two principal reasons.

First, the transformer operates at nearly constant voltage regardless of load, and its core loss and exciting current are, therefore, constant.

Second, the load current required to supply the internal losses of the transformer must pass through the reactor as well as the bushing capacitances. The net reactance drop (regulation) caused by the transformer loss is, therefore, small.

The reactor in case *B* can be built at low cost because of the low insulation requirements. This circuit arrangement has the following disadvantages.

First, the voltage across the transformer windings is a function of the burden because the reactor is in series between the burden and secondary winding. The core loss and exciting current of the transformer are nonlinear values, varying with this voltage. This leads to considerable circuit regulation with change in burden.

Second, the load current required to excite the transformer is taken directly from the tap plate of the bushing and greatly reduces the available output by causing a high capacitive reactance voltage drop at this point in the circuit.

The arrangement in case *C* entirely eliminates the separate reactor. The required inductive reactance is obtained as a leakage reactance characteristic of the transformer. This circuit is advantageous because the same high degree of accuracy and burden carrying capacity of the case *A* arrangement is obtained, yet the small size and economical construction of the case *B* arrangement is realized.

**T. M. Blakeslee** (Los Angeles Bureau of Power and Light, Los Angeles, Calif.): Mr. Clem's paper clears up considerable ambiguity that has surrounded the operation of capacitance potential devices. The Los Angeles Bureau of Power and Light has made extensive use of these devices for supplying relay potentials, hot line indication, and synchronizing on the Boulder Dam to Los Angeles transmission lines and has employed them for hot line indication and synchronizing on 110-kv and 132-kv circuits. The devices have been generally very satisfactory.

In connection with the operation of the resonant device the importance of the ground connection on the auxiliary capacitor is not always appreciated. When the device is used for carrier coupling the carrier equipment designer sometimes requires a fuse in the auxiliary-capacitor ground lead although just what protection this fuse offers to the carrier equipment is not clear. If the device is also used for supplying directional relay potential serious consequences are liable to ensue should the auxiliary-capacitor ground circuit become open by the mechanical failure of the fuse or by any other cause.

The curves presented in figure 2 of this discussion show the change in phase angle and ratio of the resonant capacitor potential device that may be expected to result from opening the auxiliary-capacitor ground lead. The curves in this figure are based on the correct adjustment of the potential device prior to the opening of the auxiliary-capacitor ground lead.

**P. O. Langguth** (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The author's paper is timely in reviewing the application of the various arrangements of capacitance potential devices. It illustrates the changes necessary to meet present day requirements of the industry although differing little fundamentally from the method originally described by us in 1928. As pointed out by the author, it is necessary to review the requirements of each application and compare them with the inherent limitations of potential devices to prevent unsatisfactory field experience. Field tests described by us in 1932 indicated satisfactory operation of the most usual relay schemes involving the several different potential devices.

The effects of electrostatic leakage and transients are probably the most important of the accuracy considerations mentioned by the author. The problem of leakage involves the design of insulation surfaces and also elimination of parts exposed to the weather. Unit construction such as illustrated in figure 3 of this discussion eliminates the hazards of exposed connections between the tapped capacitor stack and the potential network. Early experience with bushing potential devices indicated the necessity of adequate insulation of the tap connection. Succeeding designs have introduced improvements in insulation so as to eliminate varying leakage conditions and resulting varying errors with different weather conditions.

Experience has shown that the secondary transient during a fault may be more detrimental to relay operation than when a circuit is switched on and in some cases this point must be carefully considered in the design of the secondary circuit. For example, a high-speed directional element on good lines may operate incorrectly due to the damped-wave oscillation of the potential device which does not immediately go to zero. Suitable precautions in the design of the secondary circuit of the device are necessary so that these damped-wave oscillations will not cause an apparent reversal of power on the relays that should not trip. This is particularly true of the high-speed directional watt element which functions in one cycle or less and, therefore, follows the damped-wave oscillation. The magnitude of the damped wave is of assistance rather than a hindrance to the watt element provided the phase shift does not cause re-

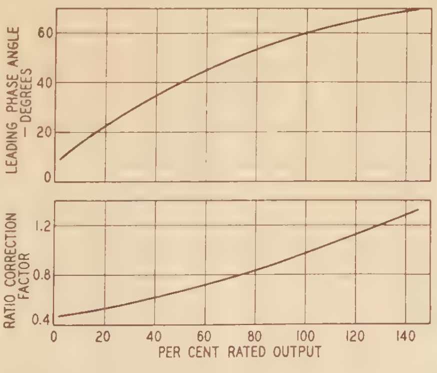

Figure 2. Typical ratio and phase-angle curves of resonant coupling-capacitor potential device resulting from opening the auxiliary-capacitor ground connection

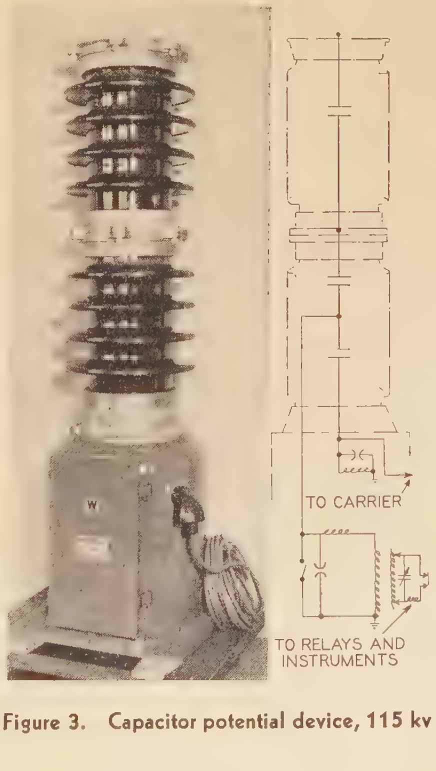

Figure 3. Capacitor potential device, 115 kv

versal and thereby undesired tripping.

We are somewhat surprised at the apparent difficulty which has been experienced with auxiliary potential transformers. We have employed them consistently in the past to obtain zero-sequence voltage. The phenomenon of two stable operating points for circuits involving capacitors and saturating reactances is well known. With proper consideration of the saturating characteristics of the potential transformers, either main or auxiliary, danger of operation in the saturated region with attendant bad wave form may be avoided. The use of auxiliary transformers to obtain zero-sequence voltage has the advantage of requiring fewer wires between the potential source and the switchboard. Attention is called to figure 5 of the paper in which the adjustment transformer is an auxiliary transformer.

The performance characteristics of the zero-sequence arrangements may be much more simply analyzed by the method of symmetrical components. This involves recognition of the fact that the output current and voltage are a function of the zero sequence voltage of the line only, so that the zero-sequence impedances of capacitors, reactors, and transformers may be used in a simple single phase equivalent circuit to determine the load voltage $E_1$ and the output, $VA$. This volt-ampere rating is a function of the primary zero-sequence voltage. This voltage varies considerably with the system conditions but for standardization of ratings it should be based on a primary zero-sequence voltage equal to the normal phase-to-neutral voltage rating of the coupling capacitor or bushings.

**D. B. Masters** (The Commonwealth & Southern Corporation, Jackson, Mich.): This paper forms a very interesting presentation of the characteristics and inherent limitations of capacitance potential devices. It is encouraging to note that great improvements have been made since the device was first developed and that it is finding an increasing field of application. Changes in design have evidently been made which decrease sources of error and permit a more accurate prediction of operating performance.

In considering their use as a source of potential for certain types of relays, it is evident that the effect of the device's limitations upon the relay's operation should be thoroughly investigated. This would seem especially pertinent with regard to reactance-type relays in which the permissible ratio error and phase-angle error are quite limited.

The gross input to the device is given in equation 10. It is our understanding that the net output is the above value less the losses. It is stated that the rating of the resonant devices are less than the possible net to insure suitable characteristics. What factors in the resonant circuit cause this? This seems to permit considerable latitude in the permissible output rating a manufacturer can assign to the device. It would seem highly desirable to define performance characteristics so that ratings of the various types of devices would be on the same basis. It would also seem desirable to give ratings in volt-amperes as is the case for potential transformers.

In the nonresonant device, the phase angle between the primary and secondary voltages can be varied from 30 degrees to 150 degrees. Is the ratio also variable and what is the range? In the resonant device it is stated that the voltage can be adjusted in one per cent steps and phase angle in one-degree steps. Over what range can these adjustments be made?

Curves and data are given which show the variation in phase-angle and ratio-correction factors for various values of operating voltage. It would be interesting to know what the effect of operating a given voltage rated device at a lower system voltage is on the phase angle and ratio for the permissible burden and accuracy; as for example, a 154-kv device operating on a 138-kv system.

In the general discussion and analysis of network circuits it is not stated whether the system neutral is grounded or isolated. Can it be said that the device is equally applicable to either system or are there certain limitations inherent to the one system not encountered in the other?

**E. H. Bancker** (General Electric Company, Schenectady, N. Y.): The old adage about "the proof of the pudding" is still as valid as when it was first written. It is actual experience with the making and using of a device that eventually results in the ironing out of the wrinkles and the establishment of confidence in its ability to perform certain functions for the benefit of society. The author of this paper has been intimately associated with potential devices almost from their inception and knows both their design characteristics and the operating characteristics which have been experienced with those in service. In his paper he makes available to everyone the experience gained from his association with these devices, so that it is possible to make an intelligent application of potential devices for the supply of voltage to different pieces of equipment with knowledge of what may be expected in the way of results. The mathematical analysis given in the appendix makes it possible to calculate the performance under almost any operating condition which users should find convenient for those instances where the usual ratio and phase-angle correction factor curves do not give sufficient information. This paper should be most helpful in applying potential devices in the future. If used with full knowledge of the results that can be obtained, potential devices become an extremely useful tool in the equipment of the utility engineer.

**J. E. Clem:** It is very pleasing to note that the discussions are in general of a constructive nature. Mr. Kennedy asks definitely whether a burden containing a closed magnetic circuit will be liable to cause instability if the characteristic is linear over the range of operating voltages. Such a burden will not cause instability. Mr. Kennedy also mentions the fact that it would be desirable to have field verification of the various conclusions reached in the paper. Some of the conclusions in the paper actually are based upon field experience, but it is admittedly desirable that a record of additional field results would be very helpful.

Mr. Farr's discussion is very helpful since he points out the three methods by which the necessary reactance may be obtained and outlines the reasons for the choice of the present standard type of construction.

It is very encouraging that Mr. Blakeslee reports very satisfactory experience from the use of these devices. A fuse in the auxiliary-capacitance ground leads serves no essential purpose and may well be omitted. The curves submitted by Mr. Blakeslee indicate that the presence of the fuse may be a liability.

It is pleasing that Mr. Langguth's discussion emphasizes several of the points brought out in the paper. However, the adjustment transformer in figure 5 is an auxiliary transformer in appearance only. In the design of the device the magnetic characteristics of the main transformer as the adjustment transformer are treated as a unit. A little further perusal of the paper will bring out the fact that the equations given for zero-sequence voltage give the same result as those which might have been obtained using the symmetrical-component method. The equations in the paper give consideration to the fact that the magnetic characteristic of the device is nonlinear.

Mr. Masters, in his discussion, asks several pertinent questions. The rating of the resonant device is less than the maximum possible output in order to keep within desirable phase-angle errors and ratio-correction factors. The present watt rating of these devices is above the maximum that has been required in any to which they have been put to date.

The ratio of the nonresonant device is subject to control as shown in figure 4 of the paper. Taps are provided so that the operating tap voltage may be of any value between 100 per cent and 50 per cent. Ordinary changes in load voltage can be taken care of by the auxiliary burden.

The resonant device is designed so that the correct voltage ratio may be obtained by means of adjustment in one per cent steps in voltage and one-degree steps in phase angle. Correct voltage ratio may be obtained at any burden within the rating of the device. The range of adjustment is selected from consideration of the tolerance permissible in the manufacture of the coupling capacitor and of the auxiliary capacitor.

The effect of operating a device designed for one circuit voltage on another circuit voltage depends, to a certain extent, upon the type of device and on the relative voltages. The foregoing, of course, refer to a complete assembly of coupling capacitor, auxiliary capacitor, if used, and potential device. The potential device itself is the same regardless of circuit voltage. A nonresonant potential device would have its output decreased directly in proportion to the decrease in circuit voltage. If the change in the circuit voltage was not too great, the output of the nonresonant device would not have to be reduced nor would its characteristic curves be changed. If the change in circuit voltage is too great it would be impossible to get correct adjustment of ratio and phase angle on a resonant device.

These devices indicate line-to-ground potential irrespective of whether the neutral is grounded, and are equally applicable to grounded or nongrounded circuits for that purpose.

# The Current-Limiting Power Fuse

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FUSES may be used on large central station and industrial systems in locations where a high interrupting capacity is required. The conventional fuse may clear a short circuit in a half cycle or several cycles. Associated apparatus is subjected to electromagnetic forces produced by the high momentary currents. Good engineering practice dictates that all disconnecting switches, contactors, motor starters, etc., shall have short-time current ratings at least equal to the initial root-mean-square fault current which the system is capable of producing at the point of installation. Where these currents are extremely high, a saving in size and expense of such apparatus can be effected if the required short-time current rating can be reduced. Many attempts have been made and accomplishment has been achieved by the use of a fuse which consistently limits the initial peak current to a fraction of that available in the circuit. The purpose of this paper is to describe the new fuse.

The economic value of a power fuse may be materially enhanced if it has, in addition to the usual requirements, the following features:

1. Adequate interrupting capacity for installation in modern central station and industrial systems.
2. Ability to limit the short-circuit current to a magnitude well below that which the system is capable of producing.
3. Ability to interrupt high currents without the generation of gas which must be discharged to the atmosphere or dissipated in a high-pressure container.
4. Silent operation with no discharge of metal parts, liquid, gas, or solid matter.
5. Suitable means of readily detecting a blown fuse.

Fuses having these desirable features in some degree, have been made available in Europe by Allgemeine Elektricitäts-Gesellschaft, Siemens-Schuckert, Brown-Boveri, Société Générale de Constructions Electriques et Méchaniques, and others, and have been partially described in European publications as indicated in the bibliography. These fuses, as manufactured by the various European companies, are similar in general design but differ in details of construction, in materials employed, and in published interrupting ratings. A new fuse has now been developed in the United States, and the authors consider it to be an improvement over the foreign fuses in these three respects. It is hoped that the material presented in this paper will be of value to the European engineers in extending their knowledge of the operating characteristics of this general type of interrupting device.

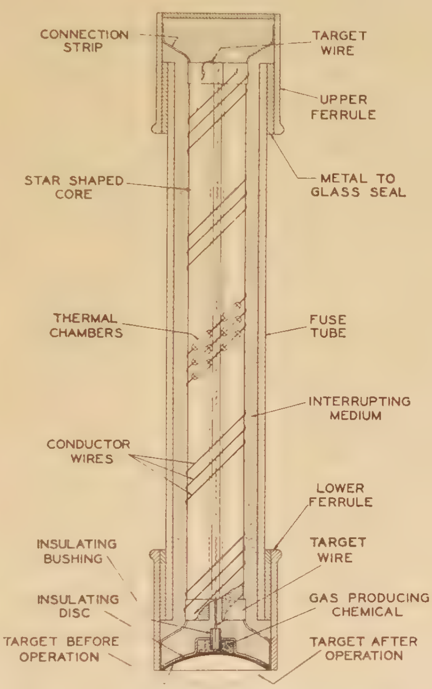

**Figure 1. Construction of the current-limiting fuse**

## Construction of Fuse Unit

The new current-limiting fuse consists of an interrupting element of one or more main conductors wound on a supporting core and embedded in a granular interrupting medium. To these parts are added a housing, terminals, indicator, and thermal chambers as shown in figure 1.

The main conductors are pure silver wires and the supporting core is high-temperature ceramic material. The ends of the wires are welded to copper connection strips which are in turn welded to the terminals or ferrules of the fuse unit. The interrupting medium is in the form of granular quartz and surrounds the conductor wires and occupies the space between the core and the Pyrex fuse tube in which the entire assembly is sealed. The granular quartz is prevented from coming in contact with a short length of the conductor wires, at their centers, by a number of thermal chambers which are formed from high-temperature ceramic material.

A target wire is welded to the upper connection strip and passes through a hole in the center of the core and terminates in a chamber at the bottom containing a small quantity of gas-producing chemical. A thin copper target is located below the chemical chamber and is arranged so that it is cupped inwardly until the blowing of the fuse causes it to reverse its curvature as indicated in figure 1.

Every material used in the current-limiting fuse, with the exception of the target chemical, is inorganic in nature and is subject to the minimum amount of corrosion and deterioration. It is possible to use a wide variety of materials for each of these components but the results of several years of research in this country and Europe indicate that the materials described in this paper provide the most efficient operation of any now available. It is reasonable to expect, however, that further research will uncover new and improved materials which will increase the efficiency of the fuse without altering the fundamental principle of circuit interruption.

## Operation

The interruption of an electric circuit by any device is accompanied by the release of system energy in the form of an arc and is followed by voltage disturbance. In a given circuit, the amount of energy released in the arc depends upon arc voltage, current, and the duration of arcing time. Modern improvements in operation of circuit-interrupting devices have been based principally upon limiting the duration of the arc and upon efficient dissipation of arc energy. A reduction in the magnitude of arc current has offered a fertile field for development which, until the advent of the current-limiting fuse, had hardly been touched.

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The authors wish to acknowledge the assistance of Otto Mayr, Allgemeine Elektricitäts-Gesellschaft, Berlin, in selecting materials, and the work of C. L. Schuck, switchgear engineering department, in establishing design data for the current-limiting fuse.

1. For all numbered references, see list at end of paper.

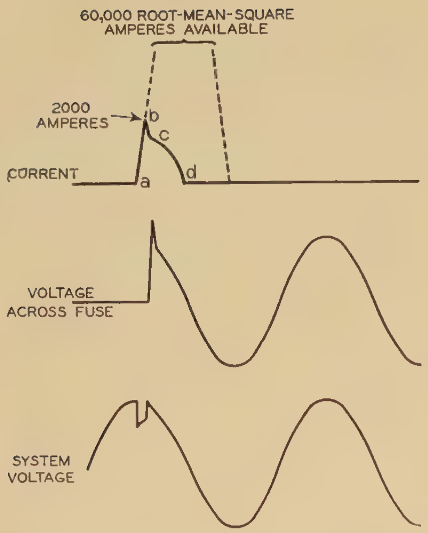

**Figure 2.** Reproduction of typical magnetic oscillogram of fuse operation

The current-limiting action of the fuse is best explained by reference to the reproduction of a typical magnetic oscillogram of a high-current test, figure 2, which shows the actual current and the current which would have existed had the fuse not been in the circuit. The short circuit begins at *a*, the silver wires volatilize and arcing begins at *b*, and the circuit is interrupted at *d*. A short-circuit root-mean-square current of 60,000 amperes is thereby limited to a maximum (peak) of 2,000 amperes.

When the silver wires volatilize at *b*, the silver vapor expands to approximately 400 times the volume originally occupied by the wire. The force of the expansion throws all of the silver vapor out of the arc path and into the space between quartz granules. It condenses on the surface of the relatively cool granules and is no longer available for current conduction. The arc is thereby confined to the small space previously occupied by the silver wires. This results in an intimate physical contact between the hot arc and the cool quartz granules which causes an exceedingly rapid transfer of heat from the arc to the quartz granules. Most of the arc energy is dissipated in this heat transfer as the pressure generated in the fuse is practically negligible.

The volatilization of the silver conductors and the sudden removal of the vapor from the arc path has the effect of suddenly inserting a very high resistance into the circuit at the instant that the silver wires melt. If the melting occurs before the short-circuit current reaches its normal initial peak magnitude, the rise of current is cut off and the current rapidly decreases to a magnitude, *c*, figure 2, well below that at which melting occurred. At point *c* sufficient resistance has been inserted to produce a power factor approximating unity and the remaining decay of the current is practically in phase with the voltage. Thus the current-limiting fuse tends to select the most favorable instant, the normal zero of both current and voltage, for final interruption with minimum disturbance.

The fuse functions as a current-limiting device on all currents which melt the conductor wires before the current reaches its initial normal peak. Obviously, the fuse cannot limit a current which reaches its peak before the conductor wires melt. Low currents cause the conductor wires to melt within the thermal chambers and to burn back toward the terminals at a rate which is dependent upon the current magnitude. On extremely low currents (currents requiring 30 minutes or more to melt the conductor wires) the arc may exist for several cycles before a gap of sufficient length to interrupt the circuit is introduced.

During the arcing period, the quartz granules in the vicinity of the arc melt and upon cooling form a hollow shell or fulgurite consisting of fused quartz and a small percentage of silver. The fulgurites have a dielectric strength, when cold, in excess of 10,000 volts per inch. Figure 3 shows a core with the main conductors before the fuse has functioned and the same core with the fulgurites formed during operation.

The operation of this novel interrupting principle at high currents inherently introduces new conditions which are not encountered with devices of a more conventional nature. The volatilization of the silver wires and the insertion of a high resistance into the circuit creates a voltage surge with a magnitude which is a function of the current at the instant of melting, the ohmic value of the resistance inserted, and the constants of the circuit. In developing this new fuse, the three factors affecting the surge voltages have been carefully studied with many cathode-ray oscillograms of both voltage and current. The crest of the surge voltage is far below the corresponding basic impulse insulation level[1] and the maximum surge voltage only slightly exceeds the crest of the 60-cycle AIEE one-minute test for rotating machines.[2]

## Design and Tests

Some of the earlier known fuses consisted of a metallic conductor surrounded by an interrupting medium of granular or powdered materials. Thousands of these older devices are now in service in the form of low-voltage cartridge fuses, high-voltage potential transformer fuses, and a limited number of high-voltage power fuses. In general, the operation of these devices produces pressures which are liable to disrupt the fuse tube if the current exceeds a few thousand amperes. The operation of the high-voltage designs on extremely low currents is questionable unless some mechanical means[3] is provided to remove the conductor from the tube. The current-limiting action of these older fuses is practically nonexistent. With this background of mediocre success previously experienced with totally enclosed fuses, the design of a high-interrupting-capacity restrained-pressure fuse of this general type seemed, at first, to be impossible. However, "the impossible" has again been accomplished by taking advantage of new and improved materials which were not available to the designers of the older fuses together with new techniques and a better understanding of the interrupting process.

The successful operation of the current-limiting fuse is dependent upon the material selected and the correct assembly and arrangement of all parts with respect to each other. The selection and arrangement of all materials was made by conducting comparative interrupting tests under controlled circuit conditions. The material or arrangement which interrupted a given current at a given voltage with the minimum length of conductor

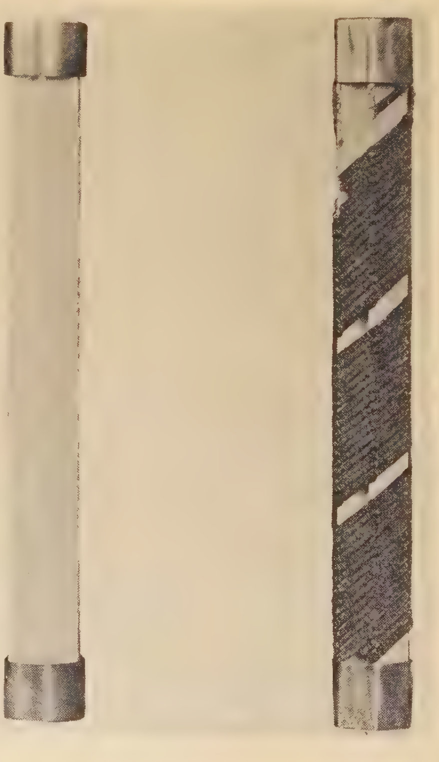

**Figure 3.** Core and conductor wires before and after operation

wire was selected as optimum. The use of a synchronous closing switch and a cathode-ray oscillograph made it possible to differentiate quite closely between materials which differed only slightly in composition.

The physical characteristics of the interrupting medium are of major importance as this material must: (*a*) remove heat from the conductor wires during normal operation, (*b*) provide a condensing surface for the metallic vapors during circuit interruption, (*c*) cool the arc during circuit interruption, (*d*) produce no gas at arc temperature, and (*e*) provide sufficient dielectric strength after circuit interruption. A number of materials were investigated and the characteristics of granular quartz were such that it was selected as the available material nearest the ideal.

The ceramic material used for the thermal chambers and the core supporting the conductors is exposed to arc temperatures at which ordinary ceramics will melt. The particular material for these parts was especially developed to maintain high resistivity at arc temperatures.

The diameter and number of wires placed in a given tube determines the current rating of the fuse and also the degree of its ability to limit the actual short-circuit current to a fraction of that available in the circuit. The length of the wires, in a given interrupting medium, determines the voltage rating of the fuse. The variation in length of single wires, of various diameters, necessary to interrupt a given voltage is indicated in figure 4. It will be noted that single small wires interrupt low currents with shorter wire lengths than those required for high currents whereas the reverse is true of larger single wires. The use of a large number of wires in parallel makes possible the design of high-current ratings with total wire sections larger than can be used with single wires. The subdivision of conductor wires not only reduces the current density in any one arc path but also provides a cascading effect during low-current operation. That is, a number of low-current arcs in parallel are unstable and one arc tends to take all of the current. If there are originally ten arcs in parallel and one of these arcs takes all of the current, the other nine are temporarily extinguished. At 10 times minimum melting current the one remaining arc is quickly and permanently extinguished. The voltage may restrike an arc successively in any or all of the other nine paths, but each arc in turn will be quickly and permanently extinguished. The use of multiple wires, therefore, reduces the length of wire required for low-current interruption to a value approaching the high-current length, indicated in figure 4, for single wires.

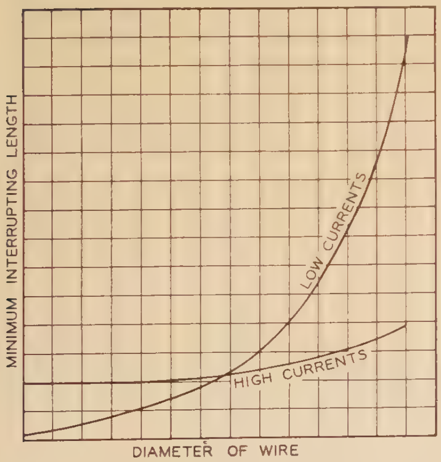

**Figure 4. Length of single wires for the interruption of a given voltage**

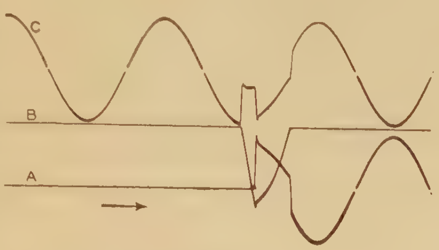

Figure 5*A*

Fuse rating—23,000 volts, 20 amperes
Test voltage—24,000 volts
Available root-mean-square current—5,000 amperes
Actual peak current—1,730 amperes
Total duration—0.0055 second
Curve *A*—Voltage across fuse
Curve *B*—Current through fuse
Curve *C*—Test generator voltage

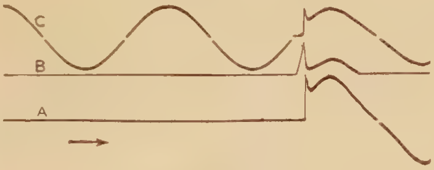

Figure 5*B*

Fuse rating—15,000 volts, 10 amperes
Test voltage—15,000 volts
Available root-mean-square current—12,500 amperes
Actual peak current—840 amperes
Total duration—0.0056 second
Curve *A*—Voltage across fuse
Curve *B*—Current through fuse
Curve *C*—Test generator voltage

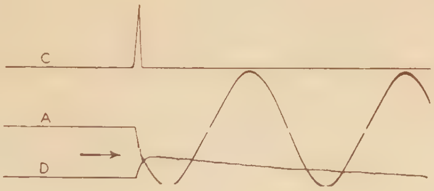

Figure 5*C*

Fuse rating—15,000 volts, 3 amperes
Test voltage—15,000 volts
Available root-mean-square current—10,400 amperes
Actual peak current—230 amperes
Total duration—0.00085 second
Curve *A*—Voltage across fuse
Curve *C*—Current through fuse
Curve *D*—Cathode-ray-oscillograph trip

**Figure 5. Typical magnetic oscillograms**

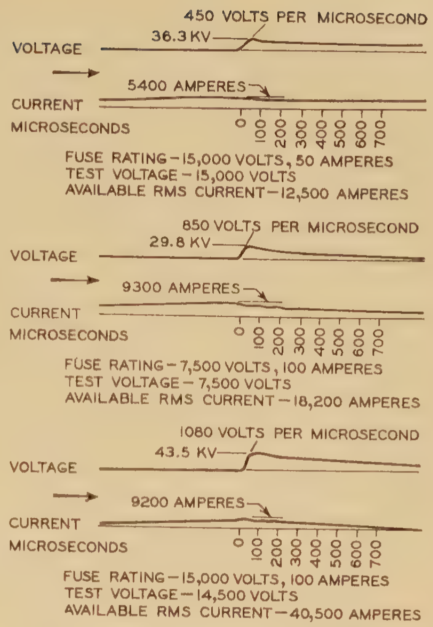

**Figure 6. Typical cathode-ray oscillograms**

Hundreds of interrupting tests at rated voltage were conducted to establish design data for a line of fuses in standard voltage ratings from 2,500 to 23,000 volts. The results of a few of these tests are given in table I. Typical magnetic oscillograms are shown in figure 5 and typical cathode-ray oscillograms are shown in figure 6. Tests were conducted with the fuse connected in the circuit near the generator terminals with practically no external capacitance or resistance. Additional tests were conducted with capacitors across the fuse to simulate a connected transmission line, and again with a series reactor tending to stiffen the circuit. The operation of the fuse was unimpaired by these conditions. The normal station rates of rise of recovery voltages were considerably modified by the fuse as indicated in table I.

## Application

The current-limiting fuse does not expel gas or metallic parts during operation. It may be completely enclosed and

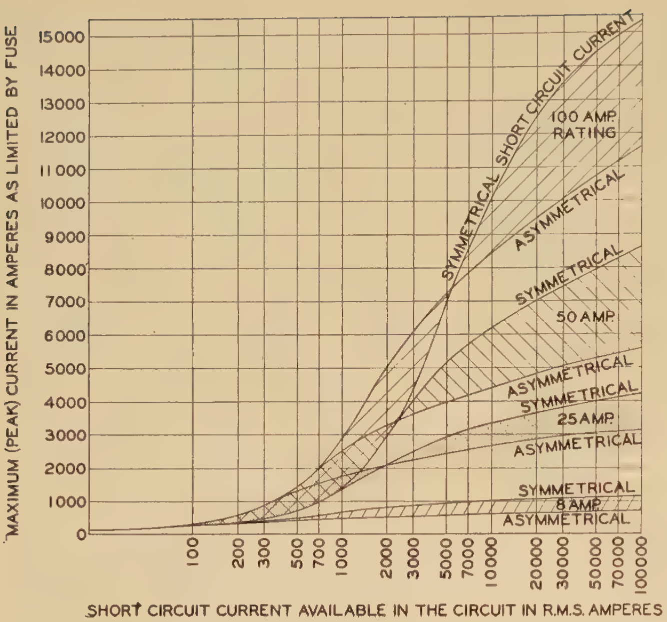

**Figure 7.** Current-limiting characteristics

mounted with the same electrical clearances used for other noninterrupting devices such as disconnecting switches and bus-bar supports. This feature makes the fuse particularly advantageous for application indoors or in metal-enclosed equipments where space economy is essential.

Since the fuse cuts off the short-circuit current before the available peak magnitude is reached, its application permits the use of associated apparatus with a lower short-time current rating than would otherwise be possible. The selection of connected apparatus may be made on the basis of the actual current which the fuse will pass, as shown in figure 7, rather than on the basis of the current which the circuit is capable of producing.

As an example of the reduction in size of connected devices made possible by the use of the current-limiting fuse, consider a single item, the disconnecting switch. A 7,500-volt 1,200-ampere disconnecting switch has a one-second rating of 60,000 amperes.[4] It is the minimum size switch which may be safely applied in a 6,600-volt 75-ampere circuit with a fault current of 35,000 amperes unless a current-limiting fuse protects the circuit. A 100-ampere fuse will limit the fault current to a peak of 13,500 amperes and permit the use of a 400-ampere switch instead of a 1,200-ampere switch. The same reasoning may be applied to all other devices in the circuit with a substantial over-all saving to the purchaser.

## Summary

1. Current-limiting fuses have been developed and tested which will interrupt a short circuit well before the current reaches the maximum value it would attain were the fuse not present.

2. These fuses have many desirable characteristics such as high interrupting capacity, silent operation, no discharge of any kind during interruption, and practically no pressure generation.

3. Such fuses have an ideal application in the protection of small-capacity circuits connected to high-power buses because the associated devices in the circuit are not subjected to the heavy momentary short-circuit current which would exist were the fuse not present.

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### Table I. Typical Test Results

| Test Number | Rating of Fuse |  | Test Voltage | *Test Current |  | Interrupting Time (Seconds) | **Recovery Rate (Volts Per Microsecond) |  |
|---|---|---|---|---|---|---|---|---|
|  | Voltage | †Current |  | Root-Mean-Square Available | Actual Peak |  | Available | Actual |
| 1 | 2,500 | 25 | 2,500 | 25,600 | 2,200 | 0.0033 | 535 | 140 |
| 2 | 2,500 | 100 | 2,500 | 25,600 | 10,000 | 0.0050 | 535 | 90 |
| 3 | 2,500 | 8 | 2,500 | 25,600 | 660 | 0.0018 | 535 | 180 |
| 4 | 2,500 | 8 | 2,500 | 46,400 | 770 | 0.0048 | 368 | 360 |
| 5 | 5,000 | 20 | 5,000 | 46,500 | 2,500 | 0.0025 | 386 | 470 |
| 6 | 5,000 | 8 | 4,200 | 77,200 | 600 | 0.0003 | 450 |  |
| 7 | 5,000 | 50 | 5,000 | 16,400 | 5,000 | 0.0008 | 883 |  |
| 8 | 5,000 | 8 | 5,000 | 1,200 | 550 | 0.0051 |  |  |
| 9 | 7,500 | 125 | 7,500 | 58,800 | 12,300 | 0.0042 | 562 | 900 |
| 10 | 7,500 | 100 | 7,500 | 58,800 | 13,700 | 0.0033 | 562 | 1,600 |
| 11 | 7,500 | 100 | 7,500 | 58,800 | 9,900 | 0.0050 | 562 | 1,100 |
| 12 | 7,500 | 100 | 8,400 | 31,800 | 9,000 | 0.0050 | 1,170 |  |
| 13 | 15,000 | 8 | 14,500 | 40,500 | 700 | 0.0042 | 600 | 1,120 |
| 14 | 15,000 | 60 | 15,000 | 9,100 | 3,400 | 0.0050 |  | 450 |
| 15 | 15,000 | 60 | 14,500 | 31,500 | 5,800 | 0.0042 | 1,060 | 1,180 |
| 16 | 15,000 | 8 | 14,500 | 40,500 | 670 | 0.0025 | 600 | 870 |
| 17 | 23,000 | 8 | 22,000 | 12,500 | 650 | 0.0042 |  |  |
| 18 | 23,000 | 8 | 22,000 | 15,000 | 935 | 0.0042 |  |  |
| 19 | 23,000 | 8 | 23,000 | 200 | 186 | 0.0107 |  |  |
| 20 | 23,000 | 10 | 25,000 | 250 | 380 | 0.0107 |  |  |

* The root-mean-square available current is the maximum root-mean-square asymmetrical current which the circuit can produce in the absence of the fuse. The actual peak current is the maximum current permitted by the fuse in the specific test. The actual peak current varies with the angle of the voltage wave at which the short circuit occurs as indicated in figure 7.

** The available recovery rate is the recovery rate which occurs in the absence of the fuse. The actual recovery rate, with the fuse in the circuit, is given only where cathode-ray measurements were made.

† Current ratings are subject to change pending the decision reached by the joint EEI-NEMA committee which is now studying this subject.

# Discussion

Table I. Initial Root-Mean-Square Unsymmetrical Short-Circuit Currents Based on Ten Per Cent Subtransient Reactance

| | | | | | |
|---|---|---|---|---|---|
| Maximum kilovolt-ampere generating capacity | 10,000 | 20,000 | 50,000 | 100,000 | 150,000 |
| Three-phase short-circuit kilovolt amperes based on 10 per cent reactance | 100,000 | 200,000 | 500,000 | 1,000,000 | 1,500,000 |
| Initial short-circuit current, root-mean-square unsymmetrical | | | | | |
| Amperes at 2,300 volts | 43,000 | 86,000 | | | |
| Amperes at 4,600 volts | 22,000 | 43,000 | 109,000 | | |
| Amperes at 6,900 volts | 14,500 | 29,000 | 72,000 | | |
| Amperes at 13,800 volts | 7,700 | 14,500 | 36,000 | 72,000 | 109,000 |

**T. G. LeClair** (Commonwealth Edison Company, Chicago, Ill.): The development of a current-limiting power fuse is an important forward step in the art of circuit interruption. The advantages of this principle for a-c circuits are comparable to the advantages of the high-speed circuit breaker on d-c circuits because of the reduction in the destructive effect of high currents.

The paper contains a very good description of what takes place when the fuse satisfactorily interrupts the circuit. However, I assume that like all other interrupting devices the fuse must have an upper limit beyond which it will fail to function. I should like to ask Messrs. Prince and Williams what determines this upper limit and what is the nature of the breakdown when the limit is exceeded. Is the limit in interrupting ability measured by the ability of the interrupting material to absorb the power loss in the arc during the period between the melting of the silver conductor and the next current zero? If so, is the interrupting ability then somewhat a variable depending upon the point on the voltage wave at which the short circuit occurs?

We frequently use fuses for the somewhat special purpose of short-circuiting a current-limiting reactor in order to reduce the duty on the circuit breaker in the event of a three-phase short circuit. Would this application with high reactance paralleling a fuse tend to increase the rate of rise of recovery voltage, which is already high due to the characteristic of the fuse itself?

Most of the discussion of this paper is naturally devoted to the essential feature of the new development, which is the speed of interruption and the consequent reduction of short-circuit current. Another feature which is important in the application of fuses, and particularly one of this type, is the time-current curve to determine the melting time of the fuse element at various percentages of normal fuse rating. It would seem to me from the fact that variations can be made in the number and size of fusible elements, that it would also be possible to obtain some measure of control on the shape and time-current curve for initial fuse melting. I would appreciate some comment from Messrs. Prince and Williams on this point.

**O. R. Schurig** (General Electric Company, Schenectady, N. Y.): One of the important advances made in the development of the current-limiting fuse is represented by the high value of the available short-circuit current in circuits which the fuse will interrupt.

As the authors have pointed out, the fuse has been successfully tested, interrupting available short-circuit currents up to 77,000 root-mean-square amperes. This is accomplished without developing high internal pressure and without expulsion effects, by so designing the fuse that circuit interruption takes place without the decomposition of any products in the fuse and that a current-limiting action occurs causing large short-circuit currents to be cut off before the peak value of the available current has been reached. The resulting benefits in respect to reduced thermal and mechanical effects in the apparatus subjected to the short-circuit currents during operation of the fuse have been brought out in the paper.

It can readily be shown that there is need for a fuse capable of interrupting the higher short-circuit currents. For this purpose, the available initial short-circuit currents (root-mean-square amperes unsymmetrical) in circuits at 2,300, 4,600, 6,900, and 13,800 volts with a maximum generating capacity within the range from 10,000 to 150,000 kva are indicated in table I on the basis of ten per cent subtransient reactance. It is of course recognized that the actual system impedance determining the magnitude of the initial short-circuit current may differ from ten per cent in many systems, considering on the one hand such factors as circuit impedance due to interconnections between separate generating stations, and arc resistance, which tend to lower the short-circuit current, and on the other hand the effects of rotating machines other than generators which tend to increase the initial short-circuit current. However, the values arrived at may be considered as fairly representative of the approximate order of magnitude for the upper limit of short-circuit currents.

It is seen from the table that a 2,300-volt system with 10,000-kva generating capacity at ten per cent subtransient reactance would have a root-mean-square unsymmetrical short-circuit of 43,000 amperes. A system with 20,000-kva generating capacity under similar conditions would have 86,000 amperes unsymmetrical root-mean-square initial short-circuit current.

Similarly a system of 50,000-kva generator capacity would have 109,000 root-mean-square amperes initial unsymmetrical short-circuit current at 4,600 volts, or 72,000 amperes at 6,900 volts.

On the same basis, a system of 100,000-kva generating capacity would have an initial root-mean-square unsymmetrical current of 72,000 amperes at 13,800 volts.

Short-circuit currents as high as those indicated in the table are no longer rare in central-station or industrial circuits. In testing the fuses at available currents as high as approximately 80,000 amperes root-mean-square unsymmetrical, the authors have not exceeded present-day maximum requirements in modern large systems. It is also significant that this current approaches the order of magnitude of the interrupting ratings of the largest oil circuit breakers specified in the NEMA oil circuit breaker standards (publication 36-38).

**G. F. Lincks** and **S. R. Smith, Jr.**, nonmember (General Electric Company, Pittsfield, Mass.): Messrs. Prince and Williams have presented a development that is a very noteworthy advancement in the art of over-current protection. In comparing this new design with existing fuses, too much attention cannot be given to the principles described which produce the necessary consistent, high degree of current limitation below that available in the circuit. Many times tests have shown existing types of oil, expulsion, and other fuses to have current-limiting characteristics. This most generally occurs with the lower current ratings of fuse links. Fuses may be divided into two groupings as regards the consistency and degree of this current-limiting ability.

The first group of fuses comprises the more commonly known oil, expulsion, and other similar types. These employ the heat generated by the arc to aid in the elongation of the arc path and to provide pressure, turbulence, a gaseous medium, or other means of rapidly decreasing the conductivity between the burned ends of the fuse to prevent re-establishment of the arc after the first current zero. While current-limiting action occurs occasionally, it is not a consistent characteristic of this group, and is never attained to the degree shown by the present design described by the authors.

The second group of fuses has two basic functions, which must be met consistently, namely,

1. Instantaneously at the end of the melting period it must in effect introduce a high resistance so as to cause an immediate limitation or decrease in current.
2. It must maintain this resistance at a sufficiently high value to limit the current appreciably below that available in the circuit in which the fuse is connected.

Available current-limiting fuses accomplish this by:

1. Instantaneous physical removal of the fusible conductor throughout the full arc length required for interruption.
2. Subjecting the arc to a high degree of cooling by a closely associated filler material which is capable of high heat absorption without loss of dielectric strength.

The efficiency of such a fuse in limiting current is dependent upon the ability of the long fusible section to volatilize instantaneously, thus immediately creating the ultimate length of arc, coupled with the characteristics of filler in the absorption of heat and the volatilized metal as indicated by the authors. Certain materials are exceedingly efficient in these respects, especially when combined with certain physical arrangements. They function instantaneously and reduce arc current, to a very low value immediately upon the melting of the fuse link, see figure 2 of the paper. Thus the arc energy is minimized to such an extent that little or no pressure is developed within the fuse unit. With less efficient fillers, the current continues to rise, after the fuse link melts, figure 1, the extent being dependent

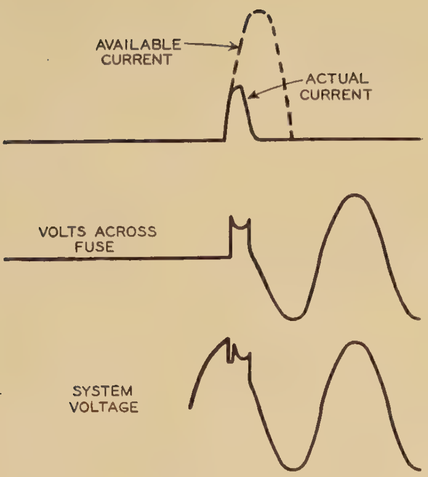


Figure 1

upon the characteristics of the fusible metal, the filler, and the physical arrangement. Naturally, the arc energy and pressure generated within the fuse unit are much greater with this increase in arc current and time. Thus while current-limiting fuses employing less efficient fillers are possible, they present real design problems in making the fuse tube or container of sufficient strength to withstand the greater stresses. So far this, coupled with economical fuse design, has imposed a definite limitation on the interrupting rating of such fuses considerably below that of the type described by the authors. Also, there is a tendency for these fuses with less efficient fillers to be affected more by circuit conditions and the point of the wave at which the fault occurs making them somewhat less consistent. This differentiation showing the marked improvement of the development described by Prince and Williams is based on four or five years' designing and testing and three years' actual service experience with current-limiting fuses of similar physical construction employing both the highly efficient and the less efficient fuse fillers.

In testing fuses in group 1, which depend upon the forces of the arc to help to extinguish it, the root-mean-square current measured at the instant arcing occurs is in general approximately the same as the symmetrical or the asymmetrical current available in the test circuit. Thus the root-mean-square current, initial in arc which the fuse actually interrupts is a true measure of the interrupting ability of fuses in group 1. This is not true with the fuses of group 2 which consistently limit the current to values appreciably below that available in the test circuit. Oscillograph records of the currents from tests with current-limiting fuses only indicate the maximum current the fuses will permit when connected in circuits having available power equal to that of the test circuit.

Therefore, in testing the current-limiting fuses of group 2, it is necessary to determine by oscillograph measurements the symmetrical and asymmetrical currents available in the circuit without the fuse as well as the instantaneous peak current the fuse will permit to flow in that circuit under both symmetrical and asymmetrical conditions. The interrupting rating should be based on the power available in the circuit. The current-limiting efficiency of the fuse is indicated by the comparison of the current permitted by the fuse in circuits of varying magnitude and the currents actually available in these circuits, see figure 7 of the paper. This is of vital importance to anyone applying these fuses from the standpoint of both economics and safety, as it indicates the stress to which connected apparatus will be subjected. Thus current-limiting fuses should have both an interrupting rating and a current-limiting rating. The interrupting rating should be based on the power available in the circuit of greatest magnitude in which the fuse functioned successfully in interrupting a dead short circuit. The current-limiting rating should be based on the maximum instantaneous peak current the fuse will permit during interruption in a circuit having available a root-mean-square current equal to the interrupting rating.

**E. J. Burnham** (General Electric Company, Schenectady, N. Y.): For a long time there has been a need for a better power fuse that could be used either indoor or outdoor and on circuits at or close to large stations where the available short-circuit current is high.

The fuse described meets these requirements exceptionally well.

In central-station work it is often desirable to connect potential transformers or control power transformers to a bus or a circuit where the available short-circuit current is very high. In the past, fuses have not been available to take care of many cases with the result that it often became a choice as to whether a circuit breaker should be used, or whether the transformer should be connected directly to the bus or line.

The first choice would mean an expensive device and the second choice would mean an interruption in case of transformer failure. The fuse described should, therefore, have a wide use as a means of fusing potential and control power transformers.

Another application for these fuses where an indoor type of fuse is desirable is for fusing the high-voltage side of metal-enclosed unit-type substations where the high-voltage side of the transformers may be 13,200 volts to 23,000 volts.

**H. L. Rawlins** (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The authors of this paper are to be congratulated for successfully working out the design of a current-limiting power fuse. The writer feels that this would be no easy task even with fuses of the same general type available from European practice.

In 1931 current-limiting fuses of the same general type as described in this paper were imported from Europe, their design studied, and exhaustive tests conducted to determine the suitability of the fuse for use in this country. As a result of this study it was decided to proceed with the development of the boric-acid fuse for the following reasons.

1. The maximum current rating and kilovolt-ampere carrying capacity of the current-limiting fuse is inherently limited. To cover adequately the field of fuse applications in this country would require two totally dissimilar lines of power fuses.

2. Where a totally enclosed and quiet operating fuse is required, a condenser can easily be attached to the boric-acid fuse.

3. The current-limiting fuse requires a long fusible section. This is undesirable from the standpoint of heat generation at currents near the melting current of the fuse. Even with inorganic material used throughout the fuse, it was feared that excessive temperature rises would occur on the contacts.

4. The benefit to the system and to the protected apparatus from the current-limiting action of the fuse was regarded as more theoretical than practical. On heavy fault currents the boric-acid fuse gives half-cycle operation. This will result in no serious disturbance to the systems and will adequately protect the lighter duty equipment usually employed on the load side of the fuse.

5. Although the interrupting action of the fuse was ideal for potential transformer protection, it was realized that the long fine fusible element could not provide adequate protection on secondary short circuits without causing unnecessary outages on magnetizing surges.

In the study of these fuses it was observed that more reliable operation was obtained on the lower current ratings where the current-limiting action was more pronounced. Although there have been many improvements in design and materials since that time, we are wondering if the maximum limit in current rating at a given voltage is the current rating at which the current-limiting action is not sufficient to insure reliable performance.

In table I actual recovery rates are listed. Are these the actual recovery rates at final interruption, or are they the rate of voltage rise at the time of peak current as shown in the cathode-ray oscillograms? Apparently, they are the latter in which case the term "recovery rate" might be questioned. It would seem that the important factors would be the available recovery rate and the maximum voltage peak occurring during interruption.

**D. C. Prince** and **E. A. Williams, Jr.:** The authors of "The Current-Limiting Power Fuse" are very grateful for the unusually constructive discussions of their paper. They feel that the replies to the many questions raised will help the ultimate users of this new device to take advantage of several operating characteristics which otherwise might not have been appreciated.

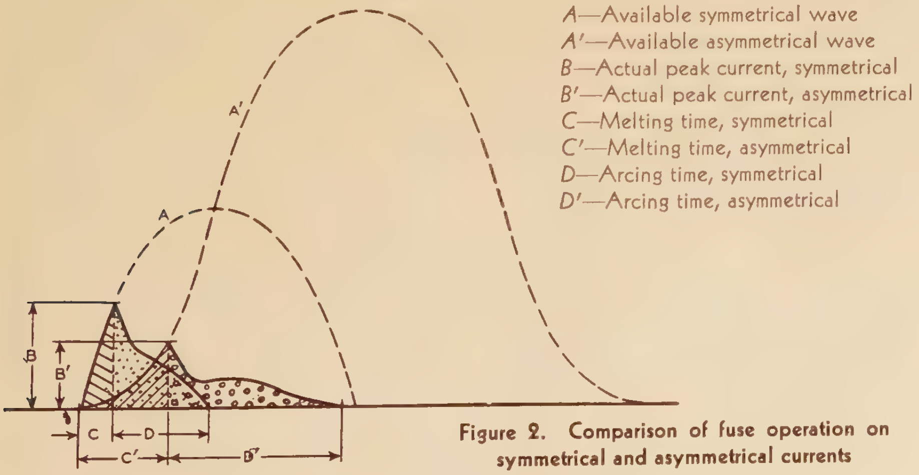
Mr. LeClair draws an interesting comparison between the new fuse and high speed d-c circuit breakers. The two devices are somewhat comparable in speed and both of them reduce the destructive effect of high currents, but the fuse is relatively more effective due to the fact that in the fuse the arc is initiated at its maximum length whereas in the breaker the arc must be drawn out to its maximum length. Since both the arc and the moving parts of the breaker have mechanical inertia, the drawing out necessarily requires a certain amount of time during which the current continues to increase. The current through the fuse does not increase after arcing begins.

The only inherent limitation upon the interrupting ability of the fuse appears to be the ability of the interrupting medium to absorb the power loss in the arc. This means that, at least theoretically, a device of this type may be designed with practically unlimited interrupting capacity by subdividing the arc into many parallel paths so that each path may take only that amount of arc energy which it is capable of absorbing. However, the number of subdivisions which can be made are limited by economics and practical manufacturing considerations. The parallel arc paths must be kept sufficiently far apart to prevent any material effect upon each other and, therefore, the size and cost of the device increases directly with the number of conductors used for any given continuous current rating. It obviously follows that the interrupting rating of the fuse can only be increased to the point at which the annual renewal cost of the fuse approaches the annual cost of operating a circuit breaker.

The interrupting capacity of any a-c interrupting device, having sufficient speed to operate within the first few cycles of short-circuit current, is more or less affected by the d-c component of the current. It is rather generally agreed that the introduction of the d-c component of current increases the interrupting duty imposed upon the conventional fuse or circuit breaker as the arc energy is a function of the total arc current. In contrast, the d-c component of currents near the interrupting capacity of the current-limiting fuse definitely decreases the interrupting duty by decreasing the initial rate of rise of the current. With the lower rate of current rise, the fuse melts at a lower instantaneous current, as illustrated in figure 2 of this discussion, and somewhat less arc energy must be absorbed by the interrupting medium. Specifically, the interrupting capacity of the fuse depends upon the point on the voltage wave at which the short circuit occurs and the fuse will interrupt considerably more current with a completely offset current wave than with a symmetrical wave.

If the current-limiting fuse described in the paper is subjected to a current or a voltage above that at which it is designed to operate, the arc energy becomes sufficient to increase the temperature of the interrupting medium (quartz granules) to a point at which it loses its dielectric strength and becomes a conductor. The short-circuit current continues until it is interrupted by a protective device at some other location in the circuit. The damage to the fuse depends entirely upon the duration of the short-circuit current. During failure there is practically no pressure generated and no explosive action. The disturbance is in no way comparable to that encountered under similar conditions with the conventional fuse or circuit breaker in which pressure is generated.

The general conception of the terms "arc voltage" and "rate of rise of recovery voltage," as applied to conventional interrupting devices, must be somewhat modified when applied to the current-limiting fuse.

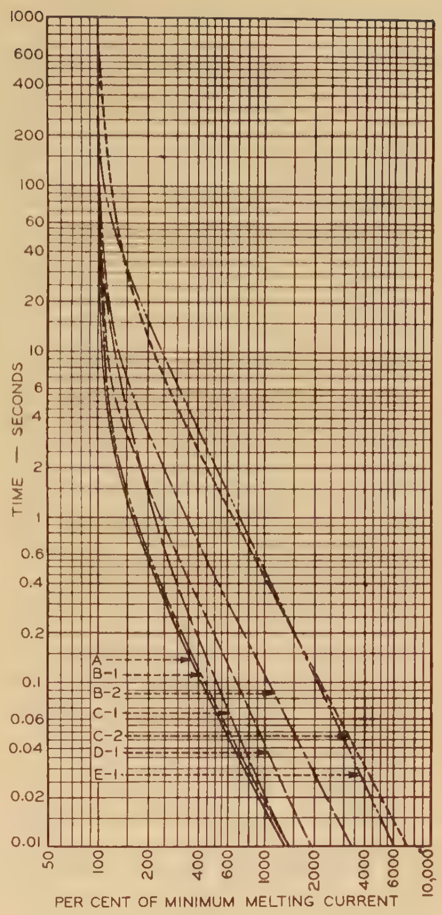


*A*—Available symmetrical wave
*A'*—Available asymmetrical wave
*B*—Actual peak current, symmetrical
*B'*—Actual peak current, asymmetrical
*C*—Melting time, symmetrical
*C'*—Melting time, asymmetrical
*D*—Arcing time, symmetrical
*D'*—Arcing time, asymmetrical

**Figure 2. Comparison of fuse operation on symmetrical and asymmetrical currents**

Arc voltage is defined as the voltage across the terminals of an interrupting device during the arcing period. The arc voltage of a conventional interrupting device is very low, relative to the open-circuit voltage, and is usually almost 90 degrees out of phase with a symmetrical short-circuit current. Just previous to arc interruption the voltage tends to be at its peak and just after interruption it rapidly "recovers" to a magnitude approaching twice its normal peak. The arc voltage of a current-limiting fuse, due to the high arc resistance, is practically equal to the open-circuit voltage except for an initial voltage surge as shown in figure 6 of the paper, and is almost in phase with the current. Arc interruption tends to occur at the zero of both voltage and current so that just after interruption the voltage does not suddenly increase but builds up along a normal-frequency wave. The voltage across the fuse "recovers" at the inception of the arc whereas the voltage across the conventional interrupting device "recovers" after the extinction of the arc. In either case, the rate of rise of recovery voltage is a function of both the device and the circuit characteristics. With the conventional device, the circuit characteristics predominate while with the current-limiting fuse the device characteristics predominate in determining the rate of rise and the magnitude of recovery voltage.

In direct reply to Mr. LeClair's question concerning the effect upon the rate of rise of recovery voltage of operating the fuse in parallel with a reactor, it may be concluded from the above discussion that the effect will be negligible.



*A*—Current-limiting fuse
*B*-1—Manufacturer *B*, fast-operating fuse
*B*-2—Manufacturer *B*, standard fuse
*C*-1—Manufacturer *C*, standard fuse
*C*-2—Manufacturer *C*, time-lag fuse
*D*-1—Manufacturer *D*, standard fuse
*E*-1—Manufacturer *E*, standard fuse

**Figure 3. Comparison of time-current curves**

A typical melting time-current curve for the current-limiting fuse is compared in figure 3 of this discussion with similar curves for conventional high-voltage power fuses. The curves are plotted in per cent of minimum melting current to eliminate differences due to methods of rating and thereby provide a common basis of comparison which is independent of rating standards. A certain amount of error is introduced by plotting the curves on a per cent of rating basis and many of the individual fuses will not exactly meet the curves. In general, the fuses of low continuous-current ratings will be somewhat faster and the fuses of high continuous-current ratings will be somewhat slower than shown by the curves. It will be noted that the melting time of the current-limiting fuse at the currents shown is not essentially different from that of existing conventional fuses and that the fuse may be co-ordinated with relays and other fuses. Since the melting time is inversely proportional to the square of the current, the speed of operation increases very rapidly as the current increases and the reputed extreme speed of the current-limiting fuse, relative to other fuses, exists principally because of its ability successfully to interrupt higher currents.

The melting time-current curves of all types of fuses, utilizing a pure fusible metal, have the same fundamental shape as they are hyperbolic in form and may be approximately determined by the general equation:

$$t = \frac{K}{i^2 - I^2}$$

where

$t$ = time to melt at any current $i$
$I$ = minimum melting current as $t$ approaches infinity
$K$ = the square of current required to melt the fuse in one second when all generated heat is retained in the fusible conductor

Since the current $I$ is arbitrarily fixed by the continuous current rating of the fuse, a variation in $K$ offers the only method of changing the relation between current, $i$, and time $t$. The magnitude of $K$ is entirely a function of the physical constants of the material used in the fusible conductors. Considering the specific case of a current-limiting fuse built into a given tube, the total cross section of the fusible conductors is determined by the current rating, the length of the conductors is determined by the voltage rating, and the number and diameter of the conductors is determined by the interrupting rating. It is, therefore, practically impossible to control the shape of the time-current curve by varying the number and size of the fusible conductors. Some measure of control may be obtained by varying the number and size of the thermal chambers shown in figure 1 of the paper.

The suggestion is made by Messrs. Lincks and Smith that the fuse be given a current-limiting rating which they define as "... the maximum instantaneous peak current the fuse will permit during interruption in a circuit having available a root-mean-square current equal to the interrupting rating." It is the opinion of the authors that a series of current-limiting curves, similar to figure 7 of the paper, showing the action of the fuses at all currents below the interrupting ratings will be of more value to the ultimate user. The proposed current-limiting ratings will then be a point on the curve rather than a separate and distinct rating.

The discussion presented by Mr. Rawlins brings out many of the reasons why three years of research, development, and testing were required to produce a new current-limiting fuse even when detail drawings, test data, and samples of certain European designs were at the disposal of the authors.

The new fuse is so designed that the temperature rise is within the limits specified by AIEE standards. The potential-transformer fuse unit is mechanically strong, it will function during secondary short circuits, and it has sufficient thermal capacity easily to withstand magnetizing surges. The reliability of the higher current ratings equals the reliability of the lower current ratings as each individual conductor is designed to interrupt approximately the same current regardless of the number of conductors, the voltage rating, or the continuous-current rating of the fuse. The current-limiting fuse requires no muffler and therefore it is unnecessary to reduce the interrupting rating for indoor application.

Mr. Rawlins has suggested that the maximum continuous-current and voltage ratings of the current-limiting fuse may be inherently limited. No such limitation is recognized except that imposed by the physical size of the unit which may be conveniently handled and economically operated.

Short-time current tests made on disconnecting switches, contactors, and current transformers have shown that these devices may be destroyed during the first half cycle of short-circuit current. The results of these practical tests merely serve to check a well-established theory and to indicate the value of a new protective instrument which limits the current in the first half cycle to a low value thereby protecting utilization equipment, of low short-time current rating, and insuring the supply system against even momentary currents of high magnitude.

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# Traveling Waves Initiated by Switching

By L. V. BEWLEY
MEMBER AIEE

THE dominating position of the lightning surge as the principal scourge of transmission lines has occupied so much attention in the technical literature that traveling waves developed from other causes have been relegated to a zone of comparative unimportance. But lately, a growing interest and curiosity concerning switching surges makes it imperative to investigate, theoretically, the possibility of initiating traveling waves from the steady state; for both the "energizing" and "de-energizing" transients associated with switching operations are calculable as traveling waves and their successive reflections. The object of this paper, therefore, is to lay the groundwork for a systematic treatment of switching surges by considering the general subject of the initiation of traveling waves from steady-state conditions. In general, such waves are started either by *closing* or *opening* a switch; and the corresponding transients may be called *closing transients* and *opening transients*, respectively. If a "dead" line is connected to a generator, the ensuing transient is called an *energizing surge*, while if a "live" line is disconnected from a generator the transient is called a *de-energizing surge.*

There are at least three methods by means of which a switching transient may be calculated, and these, in the order of their importance, as well as simplicity, will be called: (1) cancellation waves, (2) initiated waves, and (3) steady-state waves. As a matter of fact, the designation is rather loose; for all three are mutually convertible; and the line of demarcation between them is sometimes vague. Also, both "cancellation waves" and "steady-state waves" may be derived from the general equation for "initiated waves." It is rarely indeed that steady-state waves show a practical advantage over the other two, but their physical significance is intriguing, and they do provide variety in the treatment of switching problems. Very briefly:

1. *Cancellation waves* are waves of voltage (or current) impressed on the switch terminals to cancel the steady-state voltage (or current) of the switch, and thereby simulate its closing (or opening).

2. *Initiated waves* are waves computed directly from the general equations for an interruption of circuit.

3. *Steady-state waves* are pairs of fictitious waves which completely duplicate the actual steady-state distributions of voltage and current on the line and at its terminals; so that a change of circuit conditions, as by switching, may be negotiated by computing the subsequent reflections of these waves.

These three methods will now be considered in detail and illustrated by a few simple examples—often the same for each method, so as to allow a direct comparison of their relative merits.

## Cancellation Waves

An old artifice for determining the effect of "opening" a switch (probably introduced by Heaviside) is to cancel the current in the switch by impressing an equal and opposite current so that the resultant current is zero and the switch is essentially open. Of course this impressed current, suddenly applied, must flow into the connected network, and will cause some sort of a transient therein. The resultant distribution of voltage or current in the network is the sum of that due to the steady state and the transient; that is

$$\begin{pmatrix}\text{Resultant}\\ \text{distribution}\end{pmatrix} = \begin{pmatrix}\text{Steady-state}\\ \text{distribution if}\\ \text{switch is not}\\ \text{operated}\end{pmatrix} + \begin{pmatrix}\text{Transient due to}\\ \text{switch cancellation}\end{pmatrix} \quad (1)$$

This device was used by Park and Skeats[1] in their study of circuit-breaker recovery voltages. Assuming the circuit breaker to effect interruption of the circuit at a normal 60-cycle current zero, they impressed through the switch a current equal and opposite to the 60-cycle short-circuit current and calculated the transient due to it.

Likewise, of course, a switch may be "closed" by impressing an equal and opposite voltage to cancel the steady-state voltage across it. The transient due to this cancellation is easily calculated, and the resultant distribution is again given by (1).

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[1] For numbered references, see list at end of paper.

Referring to figure 1 there is shown a bus on which $n$ lines of surge impedances ($z_1$, $z_2$, . . . , $z_n$) and series impedances $W_k(p)$ (for example, current limiting reactors or transformers) terminate. There are also $m$ generators or motors with series impedances. By putting the voltage of a generator equal to zero a fixed impedance load is specified. By convention, currents (except through the switch) flowing to the bus are regarded as positive, and therefore waves on the line are forward waves if approaching the bus, or backward waves if receding away from the bus. A generalized impedance $Z(p)$, which may or may not include energy sources such as generators, charged capacitances or current-carrying inductances, is to be switched on to or off the bus. The steady-state voltages of the lines and generators are ($E_1$, $E_2$, . . ), while the steady-state currents are ($I_1$, $I_2$, . . .). The total impedance on the bus, excepting $Z(p)$, is

$$Z_0(p) = \frac{1}{\sum_1^n \frac{1}{z_k + W_k(p)} + \sum_{n+1}^{n+m} \frac{1}{W_k(p)}} \tag{2}$$

The total current flowing through the switch *away* from the bus is

$$I_0 = \sum_1^{n+m} I_k \tag{3}$$

and the steady state voltage on the bus is

$$E_0 = E_k - W_k(p) \cdot I_k \tag{4}$$

### Opening the Switch

The opening of the switch is simulated by applying the current $I_0\mathbf{1}$ through it, and this current will cause a bus voltage of

$$e_0 = Z_0(p) \cdot I_0 \tag{5}$$

The backward voltage wave appearing on the $k$th line then is

$$e_k{}' = \frac{z_k}{W_k(p) + z_k} Z_0(p) \cdot I_0 \tag{6}$$

and the transient current from the $k$th generator becomes

$$i_k = -\frac{Z_0(p) \cdot I_0}{W_k(p)} \tag{7}$$

These transient terms superimpose on the steady-state values. For example, the total voltage on the $k$th line is $(e_k{}' + E_k)$, or the total current in the $k$th generator is $(i_k + I_k)$, etc.

### Closing the Switch

The closing of the switch is simulated by impressing across its terminals a voltage $-E_0\mathbf{1}$. This voltage is in series with $Z_0(p)$ and $Z(p)$ and will, therefore, circulate a current

$$i_0 = \frac{-E_0}{Z_0(p) + Z(p)} \tag{8}$$

and the transient bus voltage will be

$$e_0 = -\frac{Z_0(p)}{Z_0(p) + Z(p)} E_0 \tag{9}$$

The voltage wave appearing on the $k$th line then is

$$e'k = -\frac{z_k}{W_k(p) + z_k} \cdot \frac{Z_0(p)}{Z_0(p) + Z(p)} E_0 \tag{10}$$

and the transient current from the $k$th generator becomes

$$i_k = \frac{1}{W_k(p)} \cdot \frac{Z(p)}{Z_0(p) + Z(p)} E_0 \tag{11}$$

These transient terms superimpose on the steady-state terms according to (1).

In addition, if $Z(p)$ includes energy sources, such as generators, charged capacitances, or current-carrying inductances; transient terms caused by the discharge of these energy sources must be calculated either from the differential equations of the circuit, taking cognizance of the initial conditions of $Z(p)$, or else by substituting $(E - E_0)$ for $E_0$ where $E$ is the voltage of $Z(p)$ at the instant of switching. It is easier to illustrate the procedure in particular examples, rather than attempt a generalized formulation.

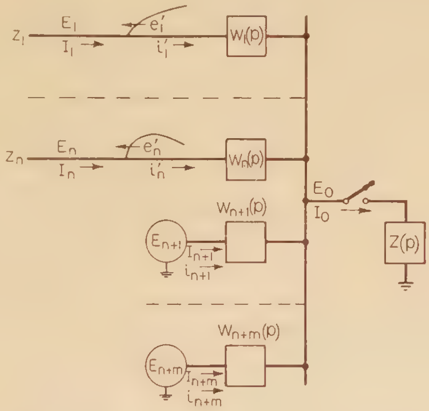


**Figure 1. Switching a generalized impedance on a bus with any number of feeders and generators**

When the cancellation waves reach the other ends of the lines, they reflect like any other traveling wave, so that the resultant distribution on the system is:

$$\left(\begin{array}{c}\text{Resultant}\\ \text{distribution}\end{array}\right) = \left(\begin{array}{c}\text{Steady-state}\\ \text{distribution}\end{array}\right) + \left(\begin{array}{c}\text{Waves of}\\ \text{cancellation}\end{array}\right) + \left(\begin{array}{c}\text{Successive}\\ \text{reflections}\end{array}\right) \tag{12}$$

A few examples will clarify the procedure.

### Sudden Grounding of a Charged Line

Figure 2 shows a line, charged to a voltage $E$, suddenly grounded at one end. The cancellation wave is obviously $e' = -E\mathbf{1}$, which also follows from (10) upon putting $W(p) = 0$, $Z(p) = 0$, and $Z_0(p) = z$. This wave, starting at the switch at the instant when it is closed, cancels the steady-state voltage $E$ at the switch thereafter. The subsequent successive reflections are given by the lattice, and the resultant voltage at the free end of the line, compounded of $E$, $-E\mathbf{1}$, and the successive reflections, is plotted on the left of the lattice to the same time scale.

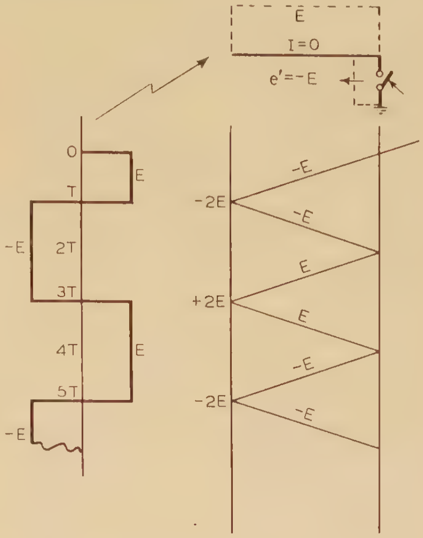


**Figure 2. Short-circuiting a charged line**

### Clearing a D-C Line Short-Circuit

In figure 3 is indicated the removal of a line-to-ground short-circuit of a d-c line. The steady-state current through the switch is $I_0 = E/R$, and therefore the cancellation wave is $e' = zI_0$ where $z$ is the surge impedance of the line. This also follows from (6) upon putting $W(p) = 0$ and $Z_0(p) = z$. When this wave reaches the generator end it reflects from the series resistor $R$ as

$$\frac{(R - z)}{(R + z)} zI_0 = \frac{(R - z)}{(R + z)} z \frac{E}{R} = \frac{(1 - z/R)}{(1 + z/R)} \frac{z}{R} E$$

The resultant voltage at the two ends of the line has been plotted for a value of $z/R = 4$. Of interest is the oscillation about normal voltage to four times normal at the opened end. This corresponds to the "inductive kick" of lumped circuits.

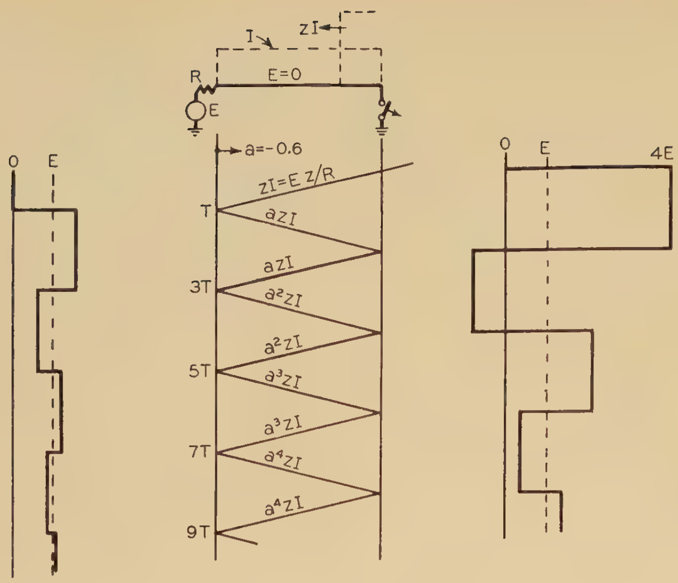


**Figure 3. Removal of a short circuit from a d-c line with series resistance**

ENERGIZING A LINE

Figure 4 shows a generator of voltage $E \cos \omega t$ and series inductance $L$ (the inductance of subtransient reactance plus the leakage inductance of any transformer, both referred to the line side) switched onto an uncharged line. If the switch is closed at the crest of normal frequency voltage, the voltage across the switch is $-E$, so that the cancellation wave across the switch is $+E$. Putting $Z_0(p) = z$ and $Z(p) = pL$ and $W(p) = 0$ in (10) there is (writing $\alpha = z/L$):

$$e' = \frac{z}{z + pL} E = E(1 - \epsilon^{-\alpha t})$$

The reflection factor at the generator end is $(pL - z)/(pL + z)$, and the $(n+1)$th reflection at the open end gives:

$$2E\left(\frac{p-\alpha}{p+\alpha}\right)^n (1 - \epsilon^{-\alpha t}) = 2E\left\{(-1)^n - \epsilon^{-\alpha t}\left[\frac{(-\alpha t)^n}{\underline{|n}} + \sum_{1}^{n} (-1)^k \frac{(-\alpha t)^{n-k}}{\underline{|n-k}} + \sum_{1}^{n}{}_{k} \sum_{1}^{k}{}_{r} \frac{\underline{|n}\,(-\alpha t)^{n-r+1}}{k\,\underline{|n-k}\,\underline{|r-1}\,\underline{|n-r+1}}\right]\right\}$$

$$= \begin{cases} 2E\{1 - \epsilon^{-\alpha t}\} & \text{for } n = 0 \\ 2E\{-1 + \epsilon^{-\alpha t}[1 + 2\alpha t]\} & \text{for } n = 1 \\ 2E\{1 - \epsilon^{-\alpha t}[1 + 2(\alpha t)^2]\} & \text{for } n = 2 \\ 2E\{-1 + \epsilon^{-\alpha t}[1 + 2\alpha t - 2(\alpha t)^2 + \frac{4}{3}(\alpha t)^3]\} & \text{for } n = 3 \end{cases}$$

These first four reflections are plotted on figure 4 for $\alpha T = 0.4$. The voltage at the open end builds up, in this case, to slightly more than double voltage. For larger values of $\alpha T$ the voltage may reach approximately, $2.5E$ (neglecting attenuation). The energizing transient is not, therefore, severe.

SYNCHRONIZING OUT OF PHASE

Suppose that a line of voltage $E_1$ is switched onto a bus of voltage $E_2$. The bus may be regarded as a small capacitance $C$, fed by a generator of series inductance $L$, as shown in figure 5. The current in the inductance prior to switching may be neglected. The voltage across the switch is $(E_1 - E_2)$ and, therefore, the cancellation voltage is $-E_0\mathbf{1} = (E_2 - E_1)\mathbf{1}$. In this case $Z_0(p) = z$ and $Z(p) = pL / (1 + CLp^2)$. The cancellation wave on the line is given by (10) as

$$e_1' = \frac{z}{z + Z(p)}(E_2 - E_1)$$

$$= \frac{z(1 + CLp^2)}{zCLp^2 + Lp + z}(E_2 - E_1)$$

$$= \left[1 - \frac{1}{n - m}\left(\frac{1 + m^2LC}{mLC}\epsilon^{-mt} - \frac{1 + n^2LC}{nLC}\epsilon^{-nt}\right)\right](E_2 - E_1)$$

in which $(-n)$ and $(-m)$ are the roots of $(zCLp^2 + Lp + z = 0)$. This same result can be obtained by superposition, first applying $(-E_1\mathbf{1})$ across the switch, and to this result adding the discharge of the generator into the line with $C$ initially charged to voltage $E_2$. For a typical case of $L = 0.10$, $C = 0.01$ microfarad, and $z = 500$ ohms there is $m = 0.20$ and $n = 0.005$; and the initial wave is

$$e_1' = (E_2 - E_1)[1 + 1.025\,\epsilon^{-0.2t} - 1.025\,\epsilon^{-0.005t}$$

This has been plotted in figure 5 for the worst possible case of $E_2 = -E_1$. The dip in the wave is due to the bus capacitance. Due to reflections, synchronizing 180 degrees out of phase may result in voltages of three to four times normal.

## Initiated Waves

In appendix I the appropriate set of simultaneous equations are derived for calculating directly the waves and transient terms initiated by switching, and it is shown that these are identical with the cancellation waves given by the previous equations (5), (6), and (7) (for *opening* a switch), and (8), (9), and (10) (for *closing* a switch). There is, then, no distinction between "initiated waves" and "cancellation waves"—merely a difference in the point of view from which they are derived—and, therefore, the previous examples may be considered to illustrate either method.

## Steady-State Waves

Steady-state waves are a generalization of the well-known fact that the ordinary a-c equations of a transmission line operating in the steady state may be expressed as a pair of waves traveling in

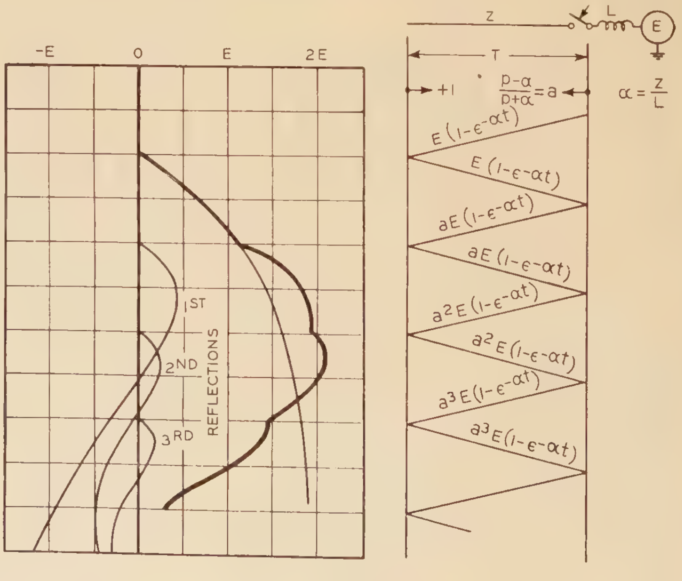


**Figure 4. Energizing a line**

opposite directions. It is shown in appendix II that these waves are (see figure 6):

$$e_s\left(t - \frac{x - x_0}{v}\right) = \frac{1}{2}\left[E\left(t - \frac{x - x_0}{v}\right) + z \cdot I\left(t - \frac{x - x_0}{v}\right)\right]$$

forward

$$e_s'\left(t + \frac{x - x_0}{v}\right) = \frac{1}{2}\left[E\left(t + \frac{x - x_0}{v}\right) - z \cdot I\left(t + \frac{x - x_0}{v}\right)\right]$$

backward

in which $E(t)$ and $I(t)$ are the steady-state voltage and current, respectively, at point $x = x_0$ on the line. It is also shown in appendix I that the "steady-state" waves not only satisfy the voltage and current distribution along the line, but also duplicate its terminal performance, if $e_s'$ be regarded as the "reflection" at one end and $e_s$ the "reflection" at the other. The associated current waves are

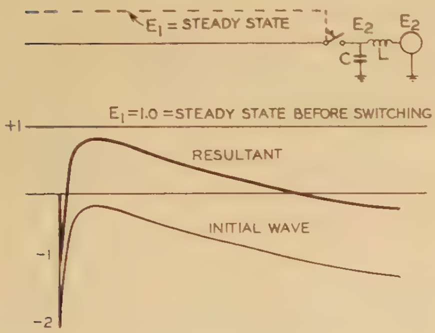


**Figure 5. Synchronizing 180 degrees out of phase**

$$i_s = \frac{e_s}{z} \text{ and } i_s' = -\frac{e_s'}{z}$$

If, now, at any point on the line the circuit is changed by a switching operation, the "steady-state" wave *receding* from that point moves away without consequence, but the "steady-state" wave *approaching* that point impinges on the new impedance introduced by the switching and gives rise to a reflection in accordance with conventional traveling-wave theory. If $Z(p)$ is the new terminal impedance, following switching, which may in general contain energy sources such as generators, charged capacitances, etc., then the reflected wave is

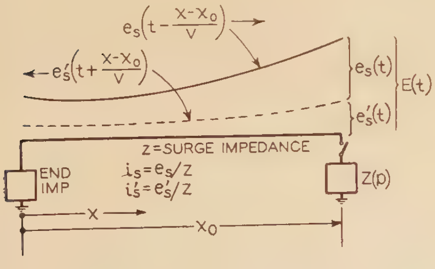


**Figure 6. Steady-state waves**

$$e' = \left(\frac{Z(p) - z}{Z(p) + z}\right) e_s + \left(\begin{array}{l}\text{Discharge of the en-}\\ \text{ergy sources of } Z(p)\end{array}\right)$$

A few simple examples will clarify the conception. Except in very simple cases it is too complicated as compared with "cancellation waves" or with "initiated waves;" because there are *two* "steady-state" waves of *finite* length (the length of the line) instead of a *single infinite* wave to deal with. This not only necessitates a double reflection lattice, but discontinuities at both head and tail of the waves. Generally, then, if successive reflections are to be taken into account, there is four times the work with "steady-state" waves as with either of the other two methods. It is shown in appendix II, however, that "steady-state" waves always combine in such a way as to yield an equivalent single infinite wave.

### SUDDEN GROUNDING OF A CHARGED LINE

Figure 7 shows an open transmission line charged to a uniform voltage $E$, suddenly shorted to ground at one end. In this case there is no steady-state current, and the voltage is constant; hence $E(t) = E$ and $I(t) = 0$ so that

$$e_s = e_s' = \frac{E}{2}$$

while

$$i_s = -i_s' = \frac{1}{2}\frac{E}{z}$$

It is seen that $e_s$ and $e_s'$ are the reflections of each other at the two ends of the open line. As soon as the switch is closed $e_s$ impinges on a grounded end, $Z(p) = 0$, causing a reflection $-E/2$, while the wave $e_s'$ moving to the left reflects therefrom as a finite rectangular wave $+E/2$. The successive reflections from the two ends shuttle back and forth, as given by the lattice, and the resultant voltage is found in the usual way by combining the successive reflections at proper time intervals, giving the oscillation shown in figure 7.

### CLEARING A LINE SHORT CIRCUIT

Figure 8 shows a d-c generator and series resistance $R$ supplying a line short-circuited at its far end. The short-circuit current is $I(t) = E/R$ and the line voltage is $E(t) = 0$, since line resistance is neglected. Therefore, the "steady-state" waves are

$$e_s = \frac{z}{R}\frac{E}{2} \text{ and } e_s' = -\frac{z}{R}\frac{E}{2}$$

At the shorted right-hand junction $e_s'$ is obviously the reflection of $e_s$. At the left-hand junction there is by (13), appendix II,

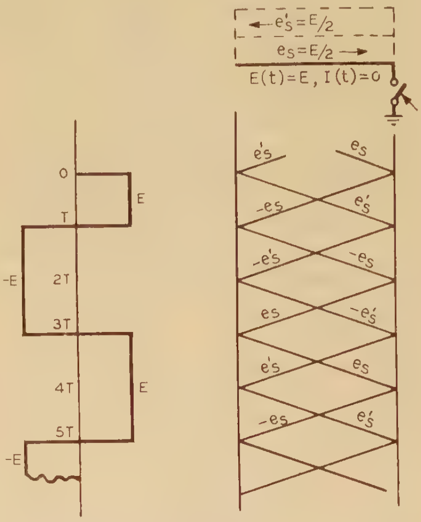


**Figure 7. Short-circuiting a charged line**

$$\begin{aligned} e_s &= \left(\frac{z}{R + z}\right) E + \left(\frac{R - z}{R + z}\right) e_s' \\ &= bE + ae_s' \\ &= \left(\frac{z}{R + z}\right) E + \left(\frac{R - z}{R + z}\right)\left(\frac{-z}{R}\frac{E}{2}\right) \\ &= \frac{z}{R}\frac{E}{2} \end{aligned}$$

in which the first term on the right is the discharge of the energy source (the generator), and the second term the reflection of $e_s'$.

$$e_s' + e_s = -\frac{z}{R}\frac{E}{2} + \frac{z}{R}\frac{E}{2} = 0$$

thus correctly satisfying the line and terminal conditions.

Now clear the short circuit, so that $e_s$ thereafter meets an open-ended line, and reflects completely. The subsequent reflections are given on the lattice of figure 8 for $z/R = 4$, in which the reflection is $e' = e$ from the right and

$$e' = bE + ae = 0.8E - 0.6e$$

from the left. The voltage at both ends of the line oscillates about normal generated voltage, but reaches four times normal at the far end.

### SUDDENLY GROUNDING AND CLEARING THE MIDPOINT OF A LINE

In figure 9 a d-c line is shown with a $R = 100$ ohm load at the far end, and a resistor $r = 100$ ohms ready to be closed in at the midpoint. The line surge impedance is $z = 400$ ohms. There are now two pairs of steady-state waves; one pair on either side of the transition point They are:

$$e_1 = e_2 = \frac{1}{2}(E + zI) = \frac{E}{2}\left(1 + \frac{z}{R}\right)$$
$$= \frac{E}{2}\left(1 + \frac{400}{100}\right) = 2.5\ E$$
$$e_1' = e_2' = \frac{1}{2}(E - zI) = \frac{E}{2}\left(1 - \frac{z}{R}\right)$$
$$= \frac{E}{2}\left(1 - \frac{400}{100}\right) = -1.5E$$

When the switch is closed, the reflection coefficients become:

$$\frac{-z}{2R + z} = \frac{-400}{200 + 400}$$
$$= -0.67 \text{ at the midpoint}$$
$$\frac{R - z}{R + z} = \frac{100 - 400}{100 + 400}$$
$$= -0.60 \text{ at the load}$$
$$-1.00 \text{ at the generator}$$

The lattice of figure 9 gives the reflection history of the four steady-state waves once the switch is closed, and the resultant voltage at the switch is shown. The voltage suddenly drops to a third of normal, and then builds up to generator voltage in a series of steps at intervals of $2T$, the time of transit of the line.

Suppose, now, after new steady-state conditions have been obtained, that the switch is opened, figure 10. For example, a line-to-ground fault clearing itself. In this case, just prior to the opening of the switch, a current $E/R$ is flowing in the right-hand section of the line, and a current $E(1/R + 1/r)$ in the left-hand section. The steady-state waves are

$$e_1 = \frac{1}{2}(E_1 + zI_1) = \frac{E}{2}\left(1 + \frac{z}{R}\right)$$
$$= \frac{E}{2}\left(1 + \frac{400}{100}\right) = +2.5$$
$$e_1' = \frac{1}{2}(E_1 - zI_1) = \frac{E}{2}\left(1 - \frac{z}{R}\right)$$
$$= \frac{E}{2}\left(1 - \frac{400}{100}\right) = -1.5$$

$$e_2 = \frac{1}{2}(E_2 + zI_2) = \frac{E}{2}\left(1 + z\frac{r + R}{rR}\right)$$
$$= \frac{E}{2}\left(1 + \frac{400}{50}\right) = 4.5$$
$$e_2' = \frac{1}{2}(E_2 + zI_2) = \frac{E}{2}\left(1 - z\frac{r + R}{rR}\right)$$
$$= \frac{E}{2}\left(1 - \frac{400}{50}\right) = 3.5$$

After the switch is closed the reflection coefficients become:

−1.0 at the generator
0.0 at the midpoint (merely a point of passage)
−0.6 at the load

The lattice of figure 10 gives the history of the reflections and the resultant voltage at midpoint. The voltage suddenly leaps to three times normal, and then oscillates about normal voltage with decreasing amplitude.

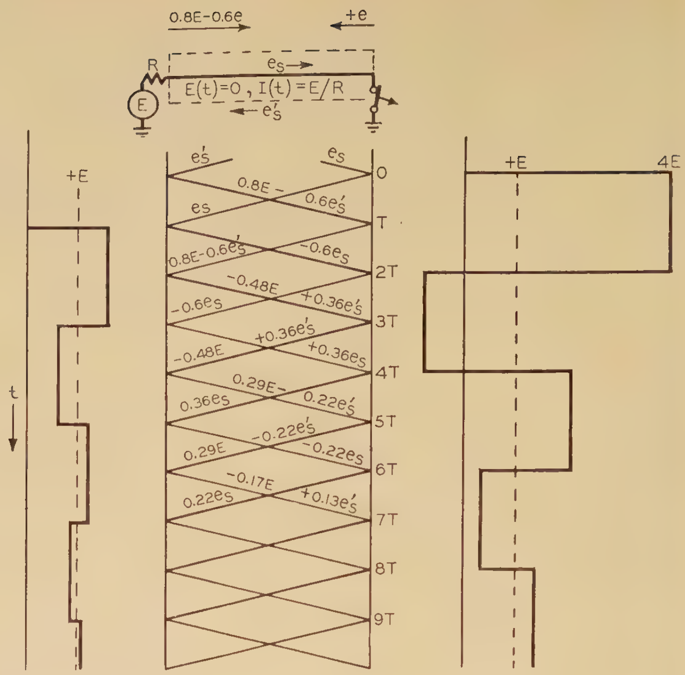
This example is somewhat similar to the operating cycle of an expulsion gap when tower footing resistance is involved.

### EQUIVALENCE OF "STEADY-STATE" WAVES TO A SINGLE INFINITE WAVE

That the pair of "steady-state" waves is always reducible, in effect, to a single infinite wave plus the steady-state distribution, is proved in general in appendix II. But it is of interest to perform the reduction in detail for a special case. The d-c line of figure 11 is carrying a direct current $I = E/R$, and the line voltage in the steady state is zero. Therefore, the steady-state waves are

$$e_s = \frac{1}{2}zI(1 - 1_T) \text{ and } e_s' = -\frac{1}{2}zI(1 - 1_T)$$

**Figure 8.** Removal of a short circuit from a d-c line with series resistance



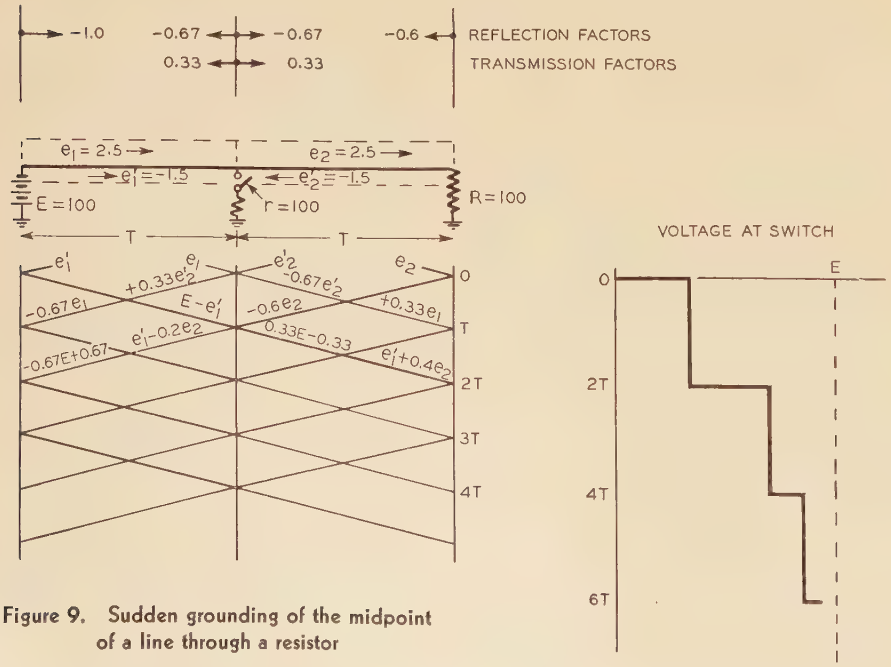


**Figure 9.** Sudden grounding of the midpoint of a line through a resistor

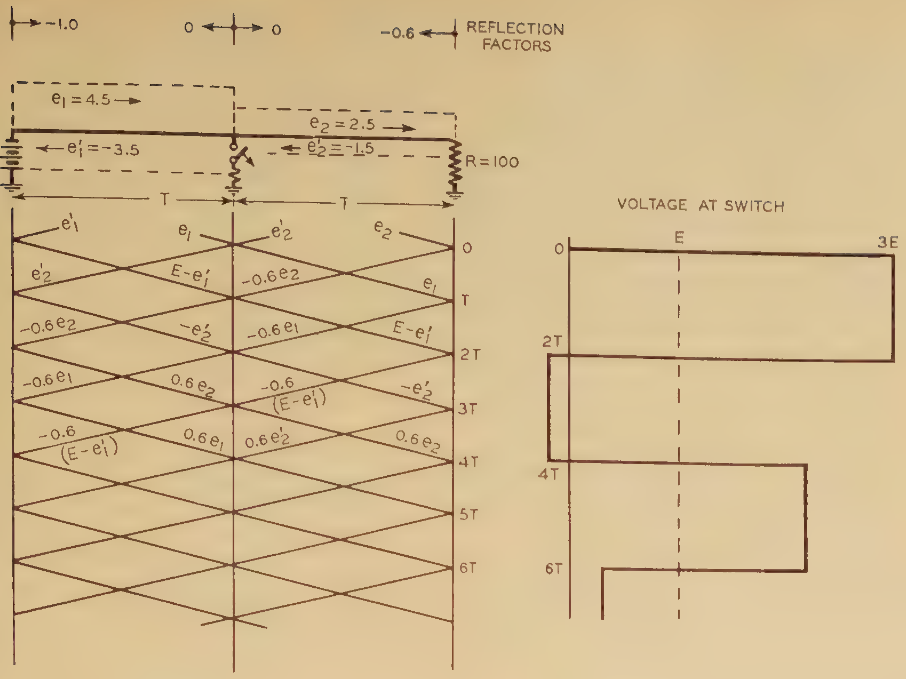


Figure 10. Removing a ground at the midpoint of a line

in which **1** is the unit function effective at $t = 0$ and $\mathbf{1}_T$ the unit function effective at $t = T$. Following the opening of the switch, causing an open circuit at the near end, the wave $e_s'$ reflects completely, while at the inductance the reflection factor is

$$a = \frac{pL_0 - z}{pL_0 + z} = \frac{p - z/L_0}{p + z/L_0} = \frac{p - \alpha}{p + \alpha}$$

The double lattice gives the history of the successive reflections of $e_s$ and $e_s'$. But in accordance with (13) appendix II, the reflection of $e_s$ at the inductance is

$$a\frac{zI}{2}(\mathbf{1} - \mathbf{1}_T) - zI\epsilon^{-\alpha t}$$

in which the second term represents the discharge of the inductance, which initially (at instant switch is opened) is carrying a current $I$, the negative sign being occasioned by the fact that the wave corresponding to this discharge is leaving the terminal (a backward wave) and must, therefore, be of negative polarity to carry with it a positive current. But

$$\left(a\frac{zI}{2} - zI\,\epsilon^{-\alpha t}\right) = \left(\frac{p - \alpha}{p + \alpha} - 2\epsilon^{-\alpha t}\right)\frac{Iz}{2}$$
$$= -\frac{zI}{2}$$

so that the reflection of $e_s$ is

$$-\frac{zI}{2}(\mathbf{1} + a\mathbf{1}_T)$$

and the first term, being of the same magnitude and polarity as $e_s'$, but infinitely long, simply follows directly behind $e_s'$ and thus prolongs it to infinity. Consequently the reflection of $e_s$ consists of a term $\left(-a\frac{zI}{2}\mathbf{1}_T\right)$ plus the conversion of $e_s'$ into an infinite wave $\left(-\frac{zI}{2}\mathbf{1}\right)$.

But $\left(-\frac{zI}{2}\mathbf{1}_T\right)$ which arrives at the inductance at time $T$, leaves the open end at the same time $t = 0$ with the reflection of $\left(-a\frac{zI}{2}\mathbf{1}\right)$, so that the combination is a single wave $(-zI\mathbf{1})$ leaving the open end at $t = 0$. The single lattice of figure 11 gives its history. Of course, the wave $-zI\mathbf{1}$ could have been inferred at once as the cancellation wave, for a current $(-I\mathbf{1})$ suddenly impressed through the switch cancels thereafter the steady-state current $I$ flowing in the switch, so that the switch is opened; and this impressed current through the surge impedance of the line carries a potential wave $(-zI\mathbf{1})$ with it.

The wave $(-zI\mathbf{1})$ arriving at the inductance at time $T$ causes a train of reflections, and according to the single lattice of figure 11 the resultant voltage at the inductance is

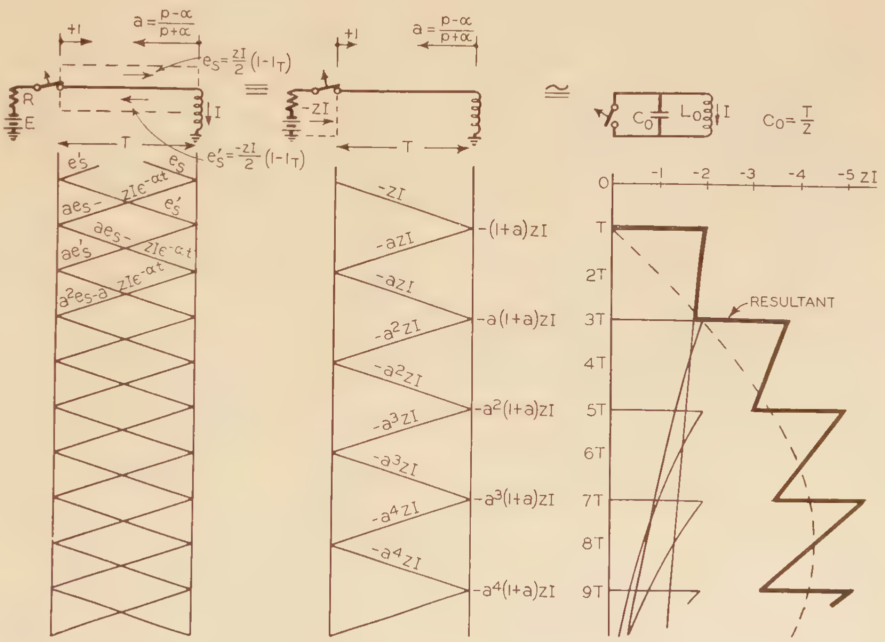
$$e = -(1 + a)[\mathbf{1}_{(T)} + a\mathbf{1}_{(3T)} + a^2\,\mathbf{1}_{(5T)} + \ldots.]zI$$

The $(n + 1)$th reflection yields

$$-(1 + a)\,a^n zI = \frac{-2p}{p + \alpha}\left(\frac{p - \alpha}{p + \alpha}\right)^n zI$$
$$= -2zI\epsilon^{-\alpha t}\sum_0^n{}_k \frac{\underline{|n}}{\underline{|n - k}} \times \sum_0^k{}_r \frac{(-\alpha t)^{n-r}}{\underline{|r}\;\underline{k - r}\;\underline{|n - r}}$$
$$= \begin{cases} -2zI\epsilon^{-\alpha t} & \text{for } n = 0 \\ -2zI\epsilon^{-\alpha t}[1 - 2\alpha t] & \text{for } n = 1 \\ -2zI\epsilon^{-\alpha t}[1 - 4\alpha t + 2\alpha^2t^2] & \text{for } n = 2 \\ -2zI\epsilon^{-\alpha t}[1 - 6\alpha t + 6\alpha^2t^2 - \frac{4}{3}\alpha^3t^3] & \text{for } n = 3 \end{cases}$$

These first few reflections and their resultant have been plotted on figure 11. It is clear that the shorter the line the

Figure 11. Reduction of "steady-state" block waves to one infinite wave and the equivalence of double and single lattices



closer together will the reflections be, and, therefore, the higher the resultant voltage.

It is of interest to obtain an approximate solution, regarding the line as a concentrated capacitance $C_0$. Since the surge impedance of the line is $z = \sqrt{L/C}$ and the velocity of propagation is $v = l/\sqrt{LC}$ it follows that the total capacitance (line of length $l$) is

$$C_0 = lC = \frac{l}{vz} = \frac{T}{z}$$

The equation for the discharge of $L_0$ with initial current $I$ into capacitance $C_0$ gives a voltage

$$e = -\frac{I}{\omega C_0} \sin \omega t = \frac{ZI}{\sqrt{\alpha T}} \sin \frac{\alpha t}{\sqrt{\alpha T}}$$

in which

$$\omega = \frac{1}{\sqrt{L_0 C_0}} = \sqrt{\frac{\alpha}{T}}$$

This approximate value of the reactor voltage has been plotted in figure 11 as a dotted curve, and is seen to be the final axis of the serrations caused by the actual reflections. For this particular example the constants were:

$z$ = 50 ohms
= surge impedance of a cable
$v$ = 500 feet/microsecond
= velocity of propagation
$l$ = 16 miles
$T = 5{,}280 \frac{l}{v} = 168$ microseconds
$L_0$ = 0.167 henry
$C_0 = T/z = 3.36$ microfarads
$\alpha = z/L_0 = 300$
$I$ = 200 amperes

The axis about which the reflections occur has a maximum of

$$\frac{zI}{\sqrt{\alpha t}} = zI\sqrt{\frac{v}{\alpha l}} = \frac{18zI}{\sqrt{\text{miles}}}$$

therefore, the maximum voltage is approximately:

| Miles of cable | 5 | 10 | 20 | 40 | 100 |
|---|---|---|---|---|---|
| Maximum voltage | 8($zI$) | 6($zI$) | 4($zI$) | 3($zI$) | 1.8($zI$) |

or higher the shorter the cable. This calculation happens to have a practical significance in connection with d-c transmission from mercury-arc-rectifier stations.

# Appendix I

## Initiated Waves

Whenever the circuit conditions are changed, traveling waves are initiated at the transition point. These waves are called *initiated waves* to distinguish them from the *steady-state* waves of appendix II. The magnitude and shape of the initiated waves depend upon the impedances at the transition point, the voltages and currents of all lines terminating there, and any new energy sources (charged capacitances, inductances with initial currents, and generators). A situation sufficiently general for most practical cases is given in figure 1, which shows $n$ lines of surge impedances ($z_1, z_2, \ldots, z_n$) which, just prior to the switching are carrying voltages ($E_1, E_2, \ldots, E_n$) and currents ($I_1, I_2, \ldots, I_n$), these being specified as functions of time at the transition point. Each line has a series impedance $W_r(p)$ connecting it to a common bus. There are also connected to this bus, through series impedances $W_r(p)$, a number of generators of voltages ($E_{n+1}, E_{n+2}, \ldots, E_{n+m}$) and delivering currents ($I_{n+1}, I_{n+2}, \ldots, I_{n+m}$). The impedance $Z(p)$ is suddenly switched onto the bus, so that (backward) traveling waves ($e_1', e_2', \ldots, e_n'$) with associated currents ($i_1', i_2', \ldots, i_n'$) are initiated on the several transmission lines, while additional currents ($i_{n+1}, i_{n+2}, \ldots, i_{n+m}$) flow from the generators.

If $Z(p)$ contains any energy sources (generators, charged capacitors, or current-carrying inductances), then the total transient voltages and currents may be regarded as the superposition:

$$\begin{pmatrix}\text{Total}\\ \text{transient}\\ \text{terms}\end{pmatrix} = \begin{pmatrix}\text{Transient terms calcu-}\\ \text{lated with zero energy}\\ \text{sources in } Z(p)\end{pmatrix} + \begin{pmatrix}\text{Transient terms calculated as}\\ \text{the discharge of the energy}\\ \text{sources in } Z(p)\end{pmatrix} \quad (13)$$

The second term on the right is easily calculated for any specific case by setting up the differential equations of the circuit, and solving for the discharge of the energy sources of $Z(p)$. The procedure is illustrated by the examples in the text.

The terms due to switching in a "quiescent" $Z(p)$, that is with zero energy sources, are calculated from a set of simultaneous equations as follows. The total voltage on any line $k$ is the sum of the transient and steady-state term,

$$e_k' + E_k = Z(p)\cdot \left[\sum_1^n (I_r + i_r') + \sum_{n+1}^{n+m} (I_r + i_r)\right] + W_k(p)\cdot(I_k + i_k') \quad (14)$$

$(k = 1, \ldots\ldots, n)$

while for any of the generators connected to the bus

$$E_k = Z(p)\cdot \left[\sum_1^n (I_r + i_r') + \sum_{n+1}^{n+m} (I_r + i_r)\right] + W_k(p)\cdot(I_k + i_k) \quad (15)$$

$(k = n + 1, \ldots, n + m)$

But for backward traveling waves

$$i_k' = -\frac{e_k'}{z_k} \quad (16)$$

Substituting (16) in (14) and (15) and rearranging

$$\left[1 + \frac{W_k(p)}{z_k}\right] e_k' + Z(p) \times \left[\sum_1^n \frac{e_r'}{z_r} - \sum_{n+1}^{n+m} i_r\right] = Z(p)\cdot I_0 + W_k(p)\cdot I_k - E_k, \; (k = 1, \ldots\ldots, n) \quad (17)$$

$$W_k(p) i_k + Z(p)\left[\sum_1^n \frac{e_r'}{z_r} - \sum_{n+1}^{n+m} i_r\right] = Z(p)\cdot I_0 + W_k(p)\cdot I_k - E_k \quad (k = n + 1, \ldots, n + m) \quad (18)$$

where

$$I_0 = \sum_1^{n+m} I_r \quad (19)$$

Equations 17 and 18 supply $(n + m)$ simultaneous equations for the determination of the $(n + m)$ unknowns ($e_1', \ldots, e_n', i_{n+1}, \ldots, i_{n+m}$).

## Opening a Switch

If the switch *opens* or *disconnects* a part of the circuit, then $Z(p) = \infty$. Equations 17 and 18 then give

$$\sum_1^n \frac{e_r'}{z_r} - \sum_{n+1}^{n+m} I_r = I_0 \quad (20)$$

which by itself is insufficient for the determination of the unknowns. But

$$e_k' - W_k(p)\cdot i_k' = e_r' - W_r(p)\cdot i_r' = -W_r(p)\cdot i_r \quad (21)$$

Hence by (16)

$$e_r' = \frac{z_k + W_k(p)}{z_r + W_r(p)} \cdot \frac{z_r}{z_k} e_k' \quad (22)$$

$$-i_r = \frac{z_k + W_k(p)}{W_r(p)} \frac{1}{z_k} e_k' \quad (23)$$

Substituting (22) and (23) in (20)

$$\frac{z_k + W_k(p)}{z_k} e_k' \times \left[\sum_1^n \frac{1}{z_r + W_r(p)} + \sum_{n+1}^{n+m} \frac{1}{W_r(p)}\right] = I_0 \quad (24)$$

hence

$$e_k' = \frac{z_k I_0}{z_k + W_k(p)} \cdot \frac{1}{\displaystyle\sum_1^n \frac{1}{z_r + W_r(p)} + \sum_{n+1}^{n+m} \frac{1}{W_r(p)}} = \frac{z_k}{z_k + W_k(p)} Z_0(p)\cdot I_0 \quad (25)$$

and

$$i_r = \frac{Z_0(p) I_0}{W_r(p)} \quad (26)$$

in which

$$Z_0(p) = \frac{1}{\displaystyle\sum_1^n \frac{1}{z_r + W_r(p)} + \sum_{n+1}^{n+m} \frac{1}{W_r(p)}} \quad (27)$$

is recognized as the total impedance as viewed from the open switch. Therefore, $Z_0(p) \cdot I_0$ is the voltage on the bus due to a sudden application of $I_0$ through the switch *in the direction of* $Z_0(p)$. But this is exactly the equivalent of cancelling the steady-state current existing in the switch prior to opening. The term $z_k/(z_k + W_k)$ in (25) is merely that proportion of the bus voltage which appears as an outgoing wave on the line. Thus when a switch is *opened* the transient term may be calculated by suddenly cancelling the switch current with an equal and opposite current (as function of time) a fact evident from first principles. Therefore:

*The effect of opening a switch may be simulated by suddenly impressing through the switch a current equal and opposite to the steady-state current through the switch.*

### Closing a Switch

Suppose that, in figure 1, the switch is about to be closed on the impedance $Z(p)$. Just prior to closing, the voltage across the switch is the voltage on the bus,

$$E_0 = E_k - W_k(p) \cdot I_k \qquad (28)$$

and the total steady-state current flowing *to* the bus is (since the switch is open)

$$I_0 = \sum_1^{n+m} I_k = 0 \qquad (29)$$

The transient voltage on the bus is

$$e_0 = e_k' - W_k(p) \cdot i_k' \qquad (30)$$

and the total transient current flowing *to* the bus is

$$i_0 = \sum_1^{n} i_k' + \sum_{n+1}^{n+m} i_k \qquad (31)$$

Substituting (28), (29), (30), and (31) in (14) and rearranging

$$e_0 = Z(p) \cdot i_0 - E_0 \qquad (32)$$

Now the total impedance as viewed from the bus, excepting $Z(p)$ is

$$\frac{e_0}{-i_0} = Z_0(p) \qquad (33)$$

and therefore (32) may be written

$$e_0 = -\frac{Z(p)}{Z_0(p)} e_0 - E_0 \qquad (34)$$

or

$$e_0 = -\frac{Z_0(p)}{Z_0(p) + Z(p)} E_0 \qquad (35)$$

But this is identically the voltage which would appear on the bus if the open switch voltage $E$ were suddenly cancelled by impressing across it a voltage $-E$. Therefore:

*The effect of closing a switch may be simulated by suddenly impressing across its terminals a voltage equal and opposite to the steady-state voltage across its terminals.*

### No Generators on Bus

If there are no generators on the bus, then equations 17, with $i_r = 0$, suffice for the determination of the voltage waves $e_k'$.

### No Generators on Bus and Zero Series Impedances

If there are no generators on the bus then $i_r = 0$, and if the series impedances are zero $W_k(p) = 0$, then equations 17 give (since $e_1' = e_2' = \ldots = e_n' = e'$ and $E_1 = E_2 = \ldots E_n = E_0$)

$$e' = \frac{Z(p) \cdot I_0 - E_0}{1 + Z(p) \sum_1^n \frac{1}{z_r}}$$

$$= \frac{z}{z + Z(p)} [Z(p) \cdot I_0 - E_0] \qquad (36)$$

in which

$$z = \frac{1}{\sum_1^n \frac{1}{z_r}} = \text{impedance of all lines in parallel} \qquad (37)$$

## Appendix II

### Steady-State Waves

It is well known that the solutions for voltage and current on a long transmission line operating in the steady state may be expressed in terms of traveling waves. Thus the vector solution for the voltage at any point $x$ (measured *negative* from the receiver) in terms of the receiver voltage $E_0$ and current $I_0$ is

$$\boldsymbol{E} = \boldsymbol{E}_0 \cosh \sqrt{\boldsymbol{zy}} x - \boldsymbol{I}_0 \sqrt{\frac{\boldsymbol{z}}{\boldsymbol{y}}} \sinh \sqrt{\boldsymbol{zy}} x \qquad (38)$$

where

$\boldsymbol{z} = r + j\omega L$
= line impedance per unit length

$\boldsymbol{y} = g + j\omega C$
= line admittance per unit length

If the losses are neglected, $r = g = 0$, and

$$\sqrt{\boldsymbol{zy}} = j\omega\sqrt{LC} = j\frac{\omega}{v}$$

$$\sqrt{\frac{\boldsymbol{z}}{\boldsymbol{y}}} = \sqrt{\frac{L}{C}} = z$$

= surge impedance of the line

$v$ = velocity of propagation

then

$$\boldsymbol{E} = \boldsymbol{E}_0 \cos\frac{\omega x}{v} - jz\boldsymbol{I} \sin\frac{\omega x}{v}$$

$$= E_0 \epsilon^{j\omega t} \cos\frac{\omega x}{v} - zI_0 \epsilon^{j(\omega t - \theta + \pi/2)} \sin\frac{\omega x}{v} \qquad (39)$$

The instantaneous value of $\boldsymbol{E}$ is the *real* of the above, or

$$E(x, t) = E_0 \cos\omega t \cos\frac{\omega x}{v} + zI_0 \sin(\omega t - \theta) \sin\frac{\omega x}{v}$$

$$= \frac{1}{2}\left[E_0 \cos\frac{\omega}{v}(x - vt) + zI_0 \cos\frac{\omega}{v}\left(x - vt + \frac{v\theta}{\omega}\right)\right] + \frac{1}{2}\left[E_0 \cos\frac{\omega}{v}(x + vt) - zI_0 \cos\frac{\omega}{v}\left(x + vt - \frac{v\theta}{\omega}\right)\right] \qquad (40)$$

This suggests the possibility of employing a pair of waves to represent the steady-state conditions on any line, whether d-c, a-c, or any other operating condition. These waves, once known, are then the *incident waves* for any change of circuit conditions, and the reflections may be calculated in routine fashion.

Let the voltage and current in the steady state at the transition point prior to switching be given as functions of time by $E(t)$ and $I(t)$, respectively. Let these conditions be specified in terms of a pair of forward and backward waves $e_s$ and $e_s'$ (the subscript $s$ implying "steady-state" waves):

$$e_s + e_s' = E(t) \qquad (41)$$

$$i_s + i_s' = I(t) \qquad (42)$$

But if $z$ is the surge impedance of the line

$$i_s = e_s/z \text{ and } i_s' = -e_s'/z \qquad (43)$$

so that (43) in (42) give

$$e_s - e_s' = z \cdot I(t) \qquad (44)$$

From (41) and (44)

$$e_s = \frac{1}{2}[E(t) + z \cdot I(t)] \qquad (45)$$

$$e_s' = \frac{1}{2}[E(t) - z \cdot I(t)] \qquad (46)$$

Thus each wave consists of a component equal to half the steady-state voltage distribution on the line, and a component equal to half the steady-state current distribution on the line; the first component reflects as from an open terminal while the second component reflects as from a grounded terminal.

The functions $e_s$ and $e_s'$ at some point $x_0$ on the line are given by (45) and (46) as *time* functions. If, however, they are to be regarded as true waves, then

$$e_s\left(t - \frac{x - x_0}{v}\right) = \frac{1}{2}\left[E\left(t - \frac{x - x_0}{v}\right) + z \cdot I\left(t - \frac{x - x_0}{v}\right)\right] \qquad (47)$$

$$e_s'\left(t + \frac{x - x_0}{v}\right) = \frac{1}{2}\left[E\left(t + \frac{x - x_0}{v}\right) + z \cdot I\left(t + \frac{x - x_0}{v}\right)\right] \qquad (48)$$

For example, taking $x_0 = 0$ and $E(t) = E_0 \cos\omega t$, $I(t) = I_0 \cos(\omega t - \theta)$, equations

(47) and (48) give the two terms of (40).

While (47) and (48) constitute the specification of the steady-state conditions on the line in terms of traveling waves, it is necessary to show that they are also compatible with the terminal impedances at the ends of the line. This is proved by showing that $e_s'$ is the natural reflection at one end of the line, and that $e_s$ is the reflection at the other end. For example, suppose the line terminates in an impedance $Z_1$ in series with a generator of voltage $E_1$. The wave $e_s'$ is composed of the reflection of $e_s$ from $Z_1$ and the discharge of $E_1$ through $Z_1$ to the line. These two terms then are:

$$\begin{aligned} e_s' &= \left(\frac{Z_1 - z}{Z_1 + z}\right) e_s + \left(\frac{z}{Z_1 + z}\right) E_1 \\ &= \left(\frac{Z_1 - z}{Z_1 + z}\right)\frac{1}{2}(E + z \cdot I) + \frac{z}{Z_1 + z} \times (E - Z_1 I) \\ &= \frac{1}{2}(E - z \cdot I) \qquad (49) \end{aligned}$$

In the same way $e_s$ may be shown to be the reflection at the other end of the line.

If, now, at any point on the line the circuit conditions are changed, as by a switching operation, the "steady-state" wave *receding* from that point moves away without consequence, but the "steady-state" wave *approaching* the point impinges on the new terminal impedance and gives rise to reflections and refractions in accordance with conventional traveling wave theory. It must be remembered, however, that when the tail of the *receding* wave reaches the terminal impedance at the other end of the line, which it is approaching, it also will cause a transient reflection there. In addition to the reflection of the approaching wave there is also a wave representing the discharge into the line of the energy sources (generators, charged capacitances, and current carrying inductances) of the terminal impedance; so that the total reflected wave from the impedance $Z(p)$ is

$$\bar{e}' = \left[\frac{Z(p) - z}{Z(p) + z}\right] e_s + \left[\begin{array}{l}\text{Discharge of the} \\ \text{energy sources} \\ \text{in } Z(p)\end{array}\right] \qquad (50)$$

If the transition point is at some intermediate point on the line, then there is a "steady-state" wave approaching the point from each direction, and the principle of superposition applies as usual.

It remains to show that the two "steady-state" waves of finite length (the length of the line) are equivalent to the single semi-infinite "initiated wave" of appendix I. The total voltage at the transition point, by (50), is

$$\begin{aligned} e &= \bar{e}' + e_s \\ &= \left[\frac{2Z(p)}{Z(p) + z}\right] e_s + \left[\begin{array}{l}\text{Energy} \\ \text{discharge} \\ \text{term}\end{array}\right] \qquad (51) \end{aligned}$$

Substituting for $e_s$ from (45) and subtracting the steady-state line voltage $E$ gives the "initiated wave"

$$e' = e - E = \left[\frac{2Z(p)}{Z(p) + z}\right]\frac{1}{2}(E + z \cdot I) + [\text{Energy discharge term}] - E$$

$$e' = \frac{z}{Z(p) + z}[Z(p) \cdot I - E] + [\text{Energy discharge term}] \qquad (52)$$

defined in equation (36) of appendix I. Now $e_s$ and $e_s'$ being finite waves of length $T$ may be represented as

$$e_s(\mathbf{1} - \mathbf{1}_T) \text{ at one end and } e_s'(\mathbf{1} - \mathbf{1}_T) \text{ at other end of line} \qquad (53)$$

that is, each as the superposition of two infinite waves of opposite sign, displaced by $T$. But since $e_s\mathbf{1}$ is the perpetual reflection of $e_s'\mathbf{1}$ at the other end of the line, and since by (41)

$$e_s\mathbf{1} + e_s'\mathbf{1} = E(t) \qquad (54)$$

it follows that the transient must be due entirely to a wave, of which $(-e_s'\,\mathbf{1}_T)$ is a component, initiated at the transition point at the instant of switching, and of which (52) is the specification. Thus the two steady-state waves of finite length are replaceable by a single infinite wave, and this infinite wave is the "initiated wave" of appendix I or the "cancellation wave" described in the text.

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## Discussion

**T. J. Carpenter** (General Electric Company, Pittsfield, Mass.): In the application of protector tubes, one of the important characteristics which must be known is the transient recovery voltage characteristic when the tube clears, as both the tube's dielectric strength and the recovery voltage are a function of time. If the recovery voltage exceeds the tube's dielectric strength, current will restart and the line will not be cleared by the tube.

From the field tests made on protector tubes, some data have been secured which show that the transient voltage due to opening a simple circuit may be quite accurately calculated even though a number of simplifying assumptions are made. Figure 1 shows the oscillogram; figure 2, the circuit, and the transcribed and calculated voltage of one test. This test was made on a 115-kv system. The phase wires of this double-circuit 30-mile line, with a single ground wire were tied together at the far end from the station making the total length of the line 60 miles. A 40,000-kva generator, 25,000-kva transformer, and the 60-mile length of line were short-circuited to ground by a fused expulsion protector tube located on the station side of the line. The protector tube cleared the circuit after a half cycle of current, and the transient voltage was measured by a cathode-ray oscillograph.

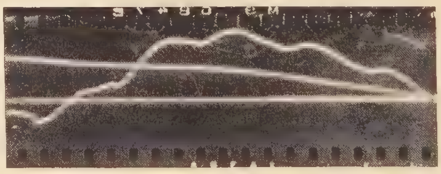

Figure 1. Oscillogram of recovery voltage

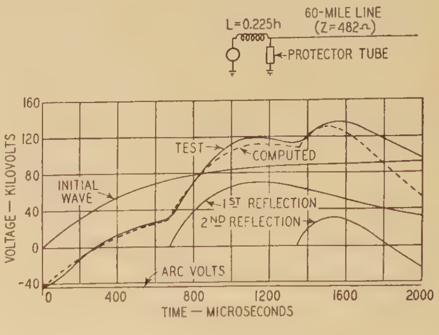

Figure 2. Comparison of computed and transcribed reflections

The equation was set up on the following assumptions: (1) the impressed voltage is considered as a constant direct voltage which is justifiable as the computation is carried out only for a fraction of a half cycle; (2) the current is treated as a sine wave; (3) the arc voltage is taken as a sine wave (used only in the determination of the current); (4) the arc voltage at current zero defines the start of the recovery voltage characteristic; (5) the station capacitance is neglected; (6) the coupling between the two circuits is neglected; and (7) the attenuation is neglected.

The derived equation for these conditions is:

$$e = -44 + 92.8[(1 - \epsilon^{-\beta t})\mathbf{1}_{0T} + 2\beta t\epsilon^{-\beta t}\mathbf{1}_{2T} + 2\beta t\epsilon^{-\beta t}(1 - \beta t)\mathbf{1}_{4T} + \ldots]$$

$e$ is the voltage in kilovolts

$\beta$ is $\dfrac{Z}{L}$

$Z$ is the surge impedance calculated from the physical constants of the line

$L$ is the equivalent inductance which determines the fault current

$\mathbf{1}_{nT}$ is the unit function effective at $t = nT$ where $T$ is the time for a wave to travel the length of the line

In plotting the equation the propagation velocity was taken to check with the oscillogram and works out to be 95 per cent of the velocity of light which checks closely with other investigations.[1]

The discrepancies between the calculated and measured recovery voltages are small, and can be accounted for by errors in the assumptions. For example, the current was distorted by the arc resistance, and the station capacitance and coupling between the looped lines and phases were neglected.

However, an exact solution does not seem to be justified, as the approximate solution gives a very good check. These simplifying assumptions make the solution much easier, and it is suggested that they be kept in mind when setting up equations for this type of problem.

### REFERENCE

1. THEORY AND TESTS OF THE COUNTERPOISE, L. V. Bewley. AIEE Lightning Reference Book, page 1392.

**R. D. Evans** and **A. C. Monteith** (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): We quite agree with Mr. Bewley as to the growing interest and curiosity in the subject of switching transients, but we believe that this interest grows out of the recognition of the increasing importance of switching surges. An example of one type of switching transient is the recovery-voltage transient, which is important in connection with the application of interrupting devices, such as circuit breakers, fuses, and protector tubes. This phase of the problem has been of particular interest to us and results from our investigations have been given in two papers, the first presented at the last summer convention and the second at the last winter convention.

In the introduction of Mr. Bewley's paper he discusses only theoretical methods applicable to the study of transients due to circuit changes. We believe that any review of methods for studying transients of this character should include mention of the method utilizing the a-c network calculator. By this method any theoretical circuit or practical system can be simulated in miniature and subjected to circuit changes corresponding to those of the system under consideration. Such an arrangement permits taking into account the effects of initiating and subsidence transients, losses, arc characteristics, etc., and the interaction of these factors. In general, we have found that it is impracticable by the use of analytical methods alone to consider all of these factors. Furthermore, as demonstrated by our recent paper presented at the winter convention, the a-c calculating board method is admirably adapted for the general study of switching transients.

We quite agree that of the three general methods discussed by Mr. Bewley the "cancellation method" is the most useful. In the practical application of this method to three-phase systems, it will be found that the resolution into symmetrical components, as outlined in our earlier paper, will constitute a simplification over "single phase" methods.

It may be inferred from the title and the treatment of the subject that transients arising from switching operations require a different treatment from that which has been developed for the study of lightning surges. It is believed that these problems are essentially the same, as both can be considered as transients arising from changes in circuits. Hence, the work on lightning surges also applies to switching surges.

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# Flashover Characteristics of Transformer Condenser Bushings

By H. L. COLE
MEMBER AIEE

TERMINAL bushings for high-voltage power transformers require many electrical tests to demonstrate their fitness for service. A vital part of the complete transformer, they operate under extreme variations of temperature and weather conditions. They are subject to all the variations in load, ambient temperature, and surges that the transformer windings receive, and in addition must be built to withstand severe attacks of ice and snow, rain and hail, hot sun, smoke, fog, dust, and dirt. They must be stronger against flashover than the protective apparatus, and must maintain their strength year in and year out. The terminal bushing is a part of the transformer and not an individual piece of apparatus; under normal service conditions it should be proportioned in strength to the winding, and should be co-ordinated with the winding under impulse voltage conditions.

The purpose of this paper is to discuss the electrical performance of bushings, particularly flashover characteristics, how they are obtained, and the relation of factory and development tests to requirements of service.

To determine the performance of transformer bushings, the following electrical tests are made:

1. Sixty-cycle, or low-frequency tests:
   - (*a*) Dry flashover.
   - (*b*) Wet flashover.
   - (*c*) One-minute hold; dry.
   - (*d*) Ten-second hold; wet.
   - (*e*) Power factor and capacity.
   - (*f*) Temperature rise under loading.
   - (*g*) Endurance tests (puncture strength under continuous high voltage at elevated temperatures).
   - (*h*) Radio interference tests.
2. Impulse tests:
   - (*i*) Full-wave strength, or minimum (50-50) flashover, with $1^1/_2$ x 40 wave.
   - (*j*) Voltage flashover—time lag curve ($1^1/_2$ x 40 wave).
   - (*k*) Flashover on steep wave front.
   - (*l*) Puncture strength, bushing immersed in oil.

The above list of electrical tests is by no means complete, but it gives the principal ones made in the development of a line of high-voltage terminal bushings. The one-minute hold test (*c*), and the power factor test (*e*), are made on all condenser bushings and are considered commercial or production tests. The remaining tests are made during development or on a representative number of the bushings only.

### (*a*) SIXTY-CYCLE DRY FLASHOVER

One of the earliest purposes of the 60-cycle dry flashover test was to demonstrate that the bushing, under comparatively short-time application of voltage, would flashover at the air end before it would puncture. It was also an indication of strength against switching surges. Before impulse tests were made, the 60-cycle dry flashover was a rough measure of the impulse strength of the air end of the bushing.

At the present time, the value of the 60-cycle dry flashover test is of minor importance in demonstrating the serviceability of the bushing. The wet flashover is the limiting feature with respect to switching surges, the one-minute test is a stronger proof of puncture strength, and the impulse flashover is a direct measure of lightning strength.

Like most of the tests, the 60-cycle dry flashover test must be made separate from the transformer. During the test the oil level at the bottom end of the bushing must be the same as in the transformer itself. The tank of oil on which the bushing is mounted for test must be sufficiently large to prevent corona disturbances at the bottom end of the bushing. The cover should have sufficient area to produce the same effect on the electric field above the tank as on the transformer.

Sixty-cycle dry flashovers of bushings, like tests on sphere gaps and rod gaps, will vary with the air density and must be corrected to a relative air density of 1.0 to obtain a comparison with the performance data recommended by the transformer subcommittee of the AIEE.[1] For all ordinary tests, where the relative air density is within ± ten per cent of unity,

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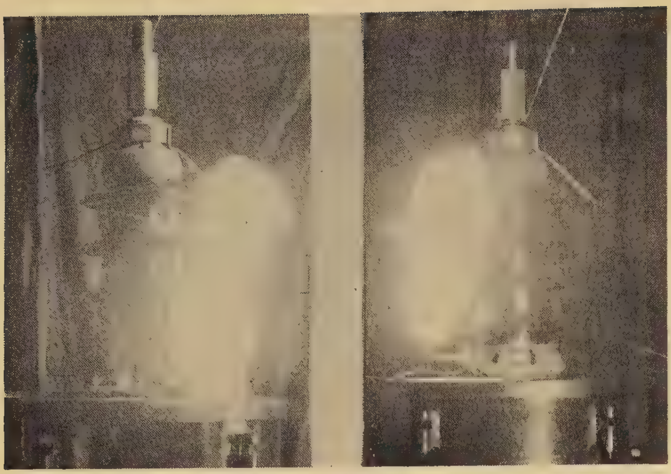
1. For all numbered references, see list at end of paper.



The flashovers shown here are on a steep wave front that reached nearly a million volts and 90,000 amperes. In these tests the bushing was equipped with a top electrode for control of positive wave flashovers, and a flange electrode for the control of negative wave flashovers

**Figure 1. Positive (left) and negative (right) impulse flashover of condenser bushing**

it is sufficiently accurate to assume that the flashover is directly proportional to the relative air density. This correction is applied to bushings of all sizes.

Sixty-cycle dry flashovers of a bushing will vary with humidity, and will increase with an increase in humidity, other factors remaining constant. The standard correction proposed by the transformer subcommittee of the AIEE[2] is that the measured flashover voltage shall be increased by three per cent for each grain that the absolute humidity falls below standard (6.5 grains per cubic foot) and decreased by three per cent for each grain above standard, to obtain the dry 60-cycle flashover for standard humidity. This correction applies only to bushings for 23-kv service and higher, and also only when they are gapped. For smaller bushings, the humidity correction is negligible. For ungapped bushings no humidity correction has been specified.

The standard for humidity, referred to in this paper as 6.5 grains per cubic foot is the same as the vapor pressure standard of 0.6085 inches of mercury now being proposed by the transformer subcommittee of the AIEE.

### (*b*) SIXTY-CYCLE WET FLASHOVER

From the standpoint of ability to withstand switching surges, the 60-cycle wet flashover value of a bushing is of more importance than the dry characteristic. The 60-cycle wet flashover is necessarily lower than the dry; the closeness to which the two can be brought together is to some extent a measure of the efficiency of the design of the bushing and its weather casing.

The following conditions have been proposed by the transformer subcommittee of the AIEE[2] for standard wet flashover tests: 12,000 ohms per centimeter cube resistance of water, with a 0.1 inch per minute precipitation at a 45-degree angle to the bushing. The correction factors for various resistivities are:

| Water Resistance Ohms Per Centimeter Cube | Correction Factor |
|---|---|
| 3,000 | 1.28 |
| 4,000 | 1.19 |
| 5,000 | 1.13 |
| 6,000 | 1.10 |
| 8,000 | 1.04 |
| 10,000 | 1.02 |
| 12,000 | 1.00 |
| 20,000 | 0.99 |

The measured flashover voltage times the correction factor gives the flashover at 12,000 ohms resistivity. This correction factor is useful because, while it is comparatively easy to regulate the amount of precipitation during a test, the control of the water resistance is difficult and would require a complicated tank supply to maintain a definite resistivity.

The *temperature* of the water affects the resistivity, and also affects the relative air density and absolute humidity. These apparently have little effect on flashover. This feature, however, has not been studied by the writer outside of the range of temperatures (10 degrees centigrade to 25 degrees centigrade) obtained in an ordinary city water supply.

### (*c*) SIXTY-CYCLE ONE-MINUTE HOLD TEST, DRY

In contrast to the flashover tests (which are mainly a check on the design of the bushing), the dry one-minute hold test is a commercial test given all bushings. The object is to check the manufacture of the bushing, the materials used, and the assembly. This test is often employed in the field to determine the suitability of a bushing for service. While the rejection of a bushing because of failure to meet this test is very rare, nevertheless it has been considered a good policy to subject transformer terminals to a higher one-minute test than they receive during the test on the windings. The one-minute hold test is made at a voltage of 75 to 90 per cent of the 60-cycle dry flashover voltage.

### (*d*) SIXTY-CYCLE TEN-SECOND HOLD TEST, WET

This test, made at a voltage of 75 to 90 per cent of the wet flashover voltage, is a special test which serves principally to demonstrate further the efficiency of the design of bushing and weather casing. It is doubtful whether such a test contributes much to the standard of bushing performance, and the test is made only in special cases.

The *following 60-cycle* tests relate to electrical performance of bushings, even though they do not come within the subject of flashover. Reference to them is made in this paper because they are fully as important as the flashover characteristics in determining the suitability of a bushing for service.

### (*e*) POWER-FACTOR AND CAPACITY TESTS

The power-factor test is a good method to determine the quality of the insulation in the bushing. This test, together with the capacity measurement, is made on all condenser bushings as a check on materials and manufacture.

### (*f*) TEMPERATURE RISE UNDER LOADING

This is a development test, to determine the safe loading for each size of bushing with a given size of cable or solid

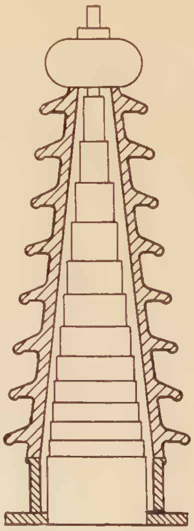


**Figure 2 (left). Condenser with uneven steps on upper end**

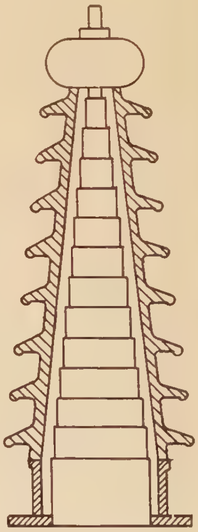


**Figure 3 (right). Condenser with even steps on upper end**

lead. In service, the lower end of the bushing is in the hottest transformer oil, and the upper end is subjected to higher than ordinary ambient temperatures. It is important to keep the temperature rise of the central part of the bushing low.

### (*g*) Endurance Tests (Puncture Strength Under Continuous High Voltage)

An important development test is that which demonstrates the strength against puncture, over long applications of voltage at high temperature. It is well known that practically all insulating materials have higher power factors at high temperatures. The total loss in a bushing must be sufficiently low so that a stable temperature condition is maintained. If the power factor is too high, the dielectric losses will increase the temperature, which in turn will increase the power factor, increasing the losses, etc., until breakdown will occur. Such a critical condition will not be caught in a one-minute test, but may take several hours to develop.

A method of making an endurance test has been to mount the bushing with the lower end in 100-degree-centigrade oil, and the upper end in 100-degree-centigrade air, and to apply a continuous 60-cycle voltage, raising the voltage ten per cent every eight hours until failure occurs. This is a severe test, but one which is without doubt justified for transformer bushings operating in high temperature localities.

### (*h*) Radio Interference Tests

The standardization of radio interference tests on high-voltage bushings is now under consideration. Tests have been made on old and new bushings, by the method proposed by the joint Edison Electric Institute, National Electrical Manufacturers Association, and Radio Manufacturers Association committees on radio interference.[3]

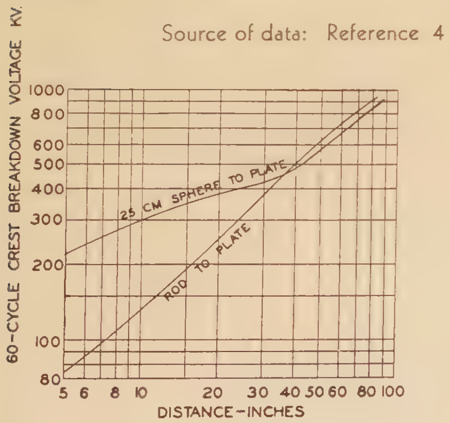


**Figure 4. Sixty-cycle flashover voltages for 25-centimeter sphere-to-plate and rod-to-plate gaps**

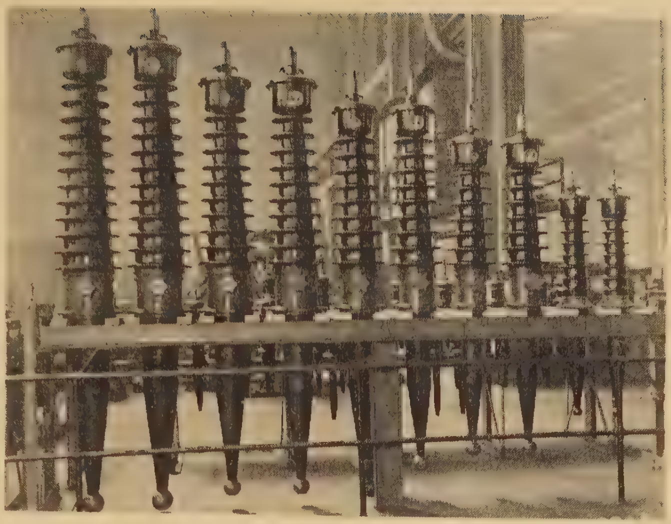


**Figure 5. A line of transformer condenser bushings, for standard voltages from 69 kv to 161 kv (inclusive)**

### (*i*) Impulse Tests; Full Wave or Minimum Flashover

Since impulse testing of transformers has become general, it has been proposed to standardize the full wave or minimum flashover voltage of transformer bushings.[1] A positive $1^1/_2$ x 40 wave has been recommended for this standardization. Until recently, the flashover strength was designated by the "equivalent gap" length of the bushing, meaning the length of standard rod gap in inches which, when connected in parallel with the bushing, would produce 50-50 flashovers between bushing and gap. At the present time the full wave strengths of bushings are measured by voltage values, by sphere gap, or cathode-ray oscillograph. From the standpoint of co-ordination of transformer winding and bushing, the bushing must not have an excessively high impulse flashover. This is also true with respect to negative full-wave values, particularly when a rod gap is used as a protective device. This point is discussed further under actual tests reported for condenser bushings.

The full-wave strength, or minimum impulse flashover of a bushing will vary with the air density and humidity.[2] The correction for air density is the same as for 60-cycle dry flashover and is applied to all bushings—the minimum impulse flashover being directly proportional to the relative air density within the limits under which ordinary tests are made. For variations in humidity, the minimum impulse flashover is $2^1/_2$ per cent lower for each grain below the standard humidity condition of 6.5 grains per cubic foot, and $2^1/_2$ per cent higher for each grain above 6.5. This correction is applied only to gapped bushings, for 23-kv service and above.

A considerable number of impulse flashover tests have been made on bushings under wet or rain conditions, with 0.1 inch per minute water precipitation. When the correction for relative air density and 100 per cent humidity is taken into consideration, the effect of the water reduces the impulse flashover not more than two or three per cent, and is considered negligible. For this reason wet impulse flashover tests are not required to demonstrate the performance of standard bushings.

### (*j*) Impulse Voltage—Time Lag Curves

The impulse flashover voltage of bushings at short time lags is important in determining the amount of protection against winding failure which the bushings will offer, and the factor of safety of the bushing itself against puncture.

### (*k*) Flashover on Steep Wave Front

With steep wave front surges, on the order of 1,000 to 2,000 kv rise per microsecond, it is important to know the flashover voltage of bushings for three reasons: (1) To determine what protection is afforded the bushing by the protective device—lightning arrester, rod gap, or line insulation; (2) to determine what protection the bushing offers the transformer winding, and (3) to determine the factor of safety of the bushing against puncture. Figure 1 shows photographs of steep wave front flashover, with heavy surge currents.

### (*l*) Impulse Puncture Strength

The impulse puncture strength of the bushing must be known in order to have complete data for the design and application of the bushing. These tests are made with the entire bushing immersed in oil.

## Condenser Bushings and Rod Gaps

Bushing flashover characteristics are closely associated with the dielectric strength of air between various types of electrodes. Since the development of impulse testing measurement of surges by means of the cathode-ray oscillograph, much data have been taken to determine the effect of condenser design, shape of bushing cap, height of flange above the cover, location and design of bushing gaps, etc., on the impulse and 60-cycle flashover of condenser bushings.

It has been known for years that the shape of the electrodes has a decided effect on the impulse flashover strength of air, and that when the positive polarity is applied to the electrode having the higher field intensity, the flashover voltage is lower. A practical study[4] of electrode shapes over a wide range of voltages, made a few years ago, has confirmed previous observations and brought out many important facts, useful in bushing design.

Some of the facts brought out or confirmed in the Bellaschi-Teague paper are:

1. The impulse flashover voltage from point to plane is lower when the point is positive and higher when the point is negative.
2. The 60-cycle flashover occurs with the positive polarity of the wave on the point.
3. A sharp projection extending out from the plane on a rod-to-plane electrode test, will reduce the impulse flashover for tests with negative polarity applied to the rod.
4. A sphere-to-plane gap has higher flashovers (60-cycle and positive waves) than a rod-to-plane gap, up to openings $3^{1}/_{2}$ times the sphere diameter. For larger openings the flashovers are less. See figure 4.

An examination of considerable data taken on condenser bushings previous to the tests described above disclosed that fundamental data on rod and rod-to-plane gaps would be desirable. Previous condenser-bushing data showed that there were several ways in which 60-cycle and impulse flashover voltages could be controlled. The tests[4] confirmed the conclusions drawn and enabled future design work to be made on a firmer basis. These conclusions are:

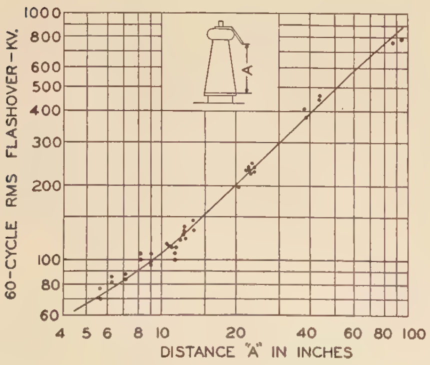


**Figure 6. Sixty-cycle dry flashover of condenser bushings**

Voltages are corrected for standard air conditions. The full line is for standard rod gaps

5. A pronounced change in both 60-cycle and impulse voltage flashover can be made by changing the length of the condenser steps on the air end of the bushing. A bushing with even steps (see figure 3) on the upper end of the condenser has a lower 60-cycle and positive wave flashover than one in which the steps are long at the top and short at the bottom (as in figure 2). For example, a 115-kv bushing with long steps at the top of the condenser, had a positive-wave flashover of 15 to 25 per cent higher, and a 60-cycle flashover 15 per cent higher than one with equal steps for the entire length of the air end. The positive full-wave flashover was higher than the negative, due to the reduction of field intensity at the top of the bushing.
6. Using the principle that a positive-wave flashover is initiated by, and is lower when a rod or point electrode is provided at the positive terminal, the impulse flashover for both positive and negative waves can be controlled independently, when desired, within practical limits. One way of accomplishing this is by means of positive and negative electrodes, mounted at 180 degrees. With this electrode or gap design, a positive wave applied to the bushing lead will flashover consistently from the cap electrode to the metal flange of the bushing. A negative wave on the lead (positive at the flange) will flash from the point electrode at the flange to the side of the bushing cap. Repeated tests will produce the same phenomena—positive wave from cap electrode to flange, negative from flange electrode to cap—even though the two distances are unequal in length as much as 10 or 15 per cent.
7. It is pointed out in the Bellaschi-Teague paper[4] that the 60-cycle flashover of sphere-to-plane electrodes is higher than a rod-to-plane, up to $3^{1}/_{2}$ times the sphere diameter.

The electric field surrounding a condenser bushing on a transformer cover is in some respects similar to sphere-to-plane or rod-to-plane electrodes.

Bushing caps vary from 4 to 16 inches in diameter, and the distances from cap to flange vary from one to six times the cap diameter. At 138-kv the opening between cap and flange is about $3^{1}/_{2}$ times the effective diameter of the cap. For higher-voltage-class condenser bushings, the 60-cycle flashover may be increased slightly by the addition of a point electrode to the cap.

### SIXTY-CYCLE TESTS ON CONDENSER BUSHINGS

A large number of 60-cycle tests on transformer condenser bushings have been made during the past four years. Some of them have been made without bushing gaps, some with special shaped electrodes, some with top and bottom electrodes at 180 degrees with each other, and others with bottom electrodes only. The data in Figures 6 and 7 give all the flashovers measured on bushings with top electrodes, or both top and bottom electrodes in place. The voltages are each an average of five flashovers, and are plotted against the vertical distance in inches from top electrode to flange.

The dry flashover voltages are corrected to relative air density = 1 and for 6.5 grains per cubic foot (0.6085 inch mercury) absolute humidity. The wet flashover voltages are corrected for water resistance in line with the Institute standard correction given above. Actual water resistances were from 3,500 to 7,500 ohms per centimeter cube during the tests.

A number of tests have been made with 0.2 inch per minute precipitation, instead of 0.1 inch per minute. Of 12 bushings tested, up to and including the 69-kv, class (approximately 24 inches length) the wet flashover for 0.2 inch per minute precipitation averages 84 per cent of that for 0.1 inch per minute; the minimum was 77 per cent, the maximum 90 per cent.

### IMPULSE TESTS ON CONDENSER BUSHINGS

Impulse flashover data on a large number of condenser bushings are given in figures 8 and 9. $1^{1}/_{2}$ x 40 waves were used. Corrections for air density and humidity have been made, in accordance with Institute standards, for all the bushings tested. In the case of positive waves, the flashovers are plotted against distances from top electrode to flange.

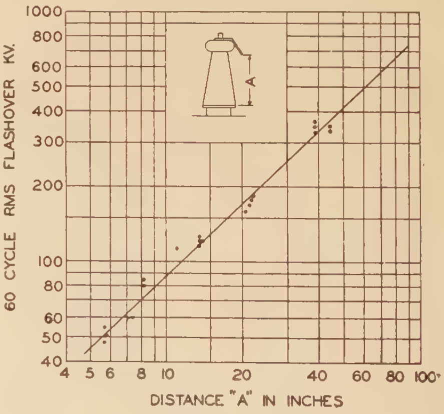


**Figure 7. Sixty-cycle wet flashover of condenser bushings**

Precipitation 0.1 inch per minute at 45 degrees to bushing. Voltages are corrected for standard water resistance of 12,000 ohms per centimeter cube

For negative waves the distances are from flange electrode to the cap.

The straight line curves in figures 8 and 9, representing two-microsecond and full-wave values are from time lag curves for standard rod gaps. These curves have been published previously, and are in the Bellaschi-Teague paper,[4] figures 3 and 4. The rod gap curves are drawn on the bushing flashover points to indicate that co-ordination of condenser bushings with rod gaps, for both positive and negative waves and down to at least two microseconds time of flashover is accomplished. The data for the bushings, as well as the rod gaps, have been taken directly from time lag curves. The time lags are measured from the 60-cycle crest voltage flashover value to the time of flashover. The variation of tests from the curves is reasonably small, considering the nature of the tests and the fact that they have been made at different times over a period of four years. The impulse flashover data are in reality more consistent than the 60-cycle data.

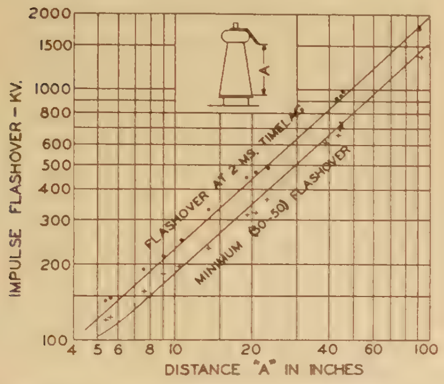


**Figure 8. Positive wave impulse flashover of condenser bushings**

$1^1/_2 \times 40$ waves were used. Voltages are corrected for standard air conditions. The full lines are for standard rod gaps

## Use of Electrodes or Gaps on Bushings

There has been some discussion in the Institute proceedings as to the need or desirability of gaps or electrodes on transformer bushings.

Several years ago the design of condenser bushings to meet the co-ordination requirements then prevailing, without the use of gaps, was considered. Even with the flexibility of design provided by the condenser bushing, where considerable range of control of the electric field is possible by location of condenser steps, it has been found desirable to use an electrode projecting out from the flange to obtain the desired negative-wave flashovers. The function of the top or cap electrode is of less importance than that of the flange electrode, as the positive-wave flashover from the plain cap of the bushing to the flange electrode is usually lower than the negative-wave flashover from flange electrode to cap.

A reference to figure 4, which is drawn from data in the Bellaschi-Teague paper[4] shows that sphere-to-plane electrodes have higher 60-cycle flashovers than rod-to-plane, for distances up to $3^1/_2$ times the sphere diameter. For longer distances the flashover is less. The same is true for positive and negative impulse flashovers. The standard requirements for bushing flashover follow closely the rod-to-rod and rod-to-plane. A bushing which has: (*a*) a low flange (bottom of porcelain close to the cover), (*b*) no electrode on the flange, and (*c*) a cap with no sharp edges or gap, will have flashover characteristics which differ from a rod-to-rod curve in a manner similar to the sphere-to-plane curve in figure 4. The extent to which it will depart from the straight line rod-to-rod curve will depend upon how closely (*a*), (*b*), and (*c*) above are met. Whether the flashover will be above, or below the straight line curve will depend upon the relative diameter (effective) of cap and height of porcelain.

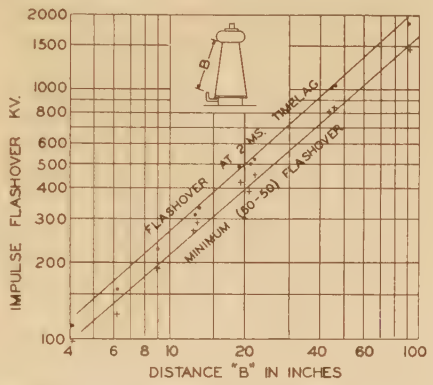


**Figure 9. Negative wave impulse flashover of condenser bushings**

$1^1/_2 \times 40$ waves were used. Voltages are corrected for standard air conditions. The full lines are for standard rod gaps

From the standpoint of uniformity of design, co-ordination of bushing with protective apparatus, and possible protection to the winding offered by the bushing, the use of a gap on the flange of bushing seems desirable. The writer's experience has been that bushings with gaps have less erratic flashover values (see figure 10, showing negative impulse-time lag curves for bushing with and without gap at flange). A gap will often prevent a flashover to other metal parts of the transformer, such as caps of adjacent bushings or grounded metal projecting above the transformer cover. This is especially true of the gap at the flange of the bushing. A gap is a ready means for fixing the flashover values and adjusting the flashover for special applications. The humidity correction factor is more definitely known for gapped bushings.

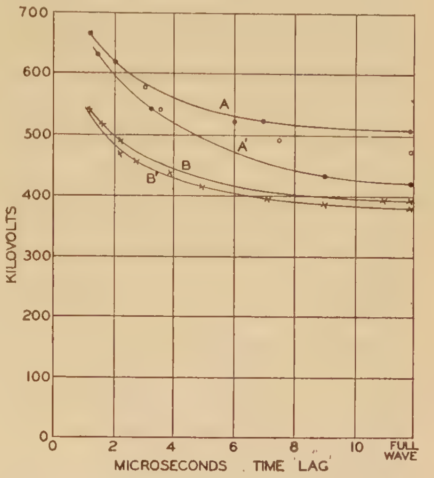


**Figure 10. Impulse flashover-time lag curve of bushing, showing spread of points**

*A-A'*—Without gap at flange
*B-B'*—With gap at flange
Tests made with negative $1^1/_2 \times 40$ wave

Co-ordination of bushing and winding becomes practical when a gap is used. For example, a 138-kv transformer winding has a safe impulse test strength (based on an impulse ratio of 2.2) of 860 kv. If we select a bushing with an equivalent gap of 44 inches (the previous recommended standard), it will have a 60-cycle dry flashover (from figure 6) of approximately 425 kv, a 60-cycle wet flashover (figure 7) of approximately 350 kv. The impulse flashovers would be (from figures 8 and 9) positive minimum flashover 700 kv, negative minimum flashover 800 kv. These data show that without allowance for factor of safety in the winding insulation the bushing is co-ordinated with the winding for full waves and for waves chopped by the bushing at fairly long time lags (three to six microseconds). In other words, the bushing is substantially another co-ordinating gap, of similar characteristics but with slightly higher flashover values than the former standard gap.

The writer knows of only two cases of bushing flashovers on modern power transformers during the past three years. In neither case were the windings damaged. The bushings were gapped. Without gaps, these bushings would have had from 5 to 10 per cent higher positive-wave flashover, and 25 to 50 per cent higher negative wave flashover.

In conclusion, it is desired to point out that the data in this paper refer only to bushings for transformers. The recommendations and conclusions should not be interpreted as recommending the same practice on bushings for other apparatus.

## Conclusions

1. It is necessary to make many electrical tests to prove that bushings will meet service conditions.
2. Correction factors for flashover tests of gapped bushings, as proposed by the AIEE transformer subcommittee, hold within reasonable limits as indicated by tests over a considerable period and under widely varying conditions.
3. Present correction factors for humidity do not apply to ungapped bushings unless they are provided with the equivalent in the form of sharp or square corners.
4. Flashover values for ungapped bushings may be erratic or in some cases lower than when equipped with gaps.
5. Ungapped bushings may have very high negative-wave flashovers, and may result in flashovers directly to other windings rather than to ground unless excessive distances are taken.
6. Properly gapped, bushings meet all of the characteristics at present recommended by the AIEE transformer subcommittee. The fact that special electrodes or gaps are furnished may not result in any reduction in guaranteed strengths.
7. Bushings having performance substantially equivalent to the "equivalent gaps" proposed for bushings can furnish a considerable margin of protection to transformer windings without encroaching upon the factor of safety. It is probable that, including the factor of safety, and for a single surge, high-voltage surges at short time lags could be withstood.
8. It is desirable, under normal conditions, to use bushings having characteristics as nearly as possible equal to the "equivalent gaps" previously proposed, because much protection at no cost is thereby obtained, and the location of the initial flashover can be controlled.

## References

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# Discussion

**R. E. Pierce** (Ebasco Services Inc., New York, N. Y.): Regarding the question of whether or not bushings should be provided with gaps, the author's reasons for advocating their use are sound. They are a measure of protection to the transformer winding, and control the location of any flashovers.

However, because they do fix the location of flashovers, I feel very strongly that the gap electrodes should not be integral with the bushing itself, as illustrated in the paper, as experience has shown that a gap in this position is certain to cause thermal damage to the porcelain in the event of flashovers, but rather that the gap electrodes should be mounted or arranged on the bushing terminal and transformer cover in such a way that any arcing will be at a good distance from and preferably above the porcelain. Practically, therefore, complete knowledge of the characteristics, correction factors, etc., for the ungapped bushings is essential, in order to intelligently coordinate the insulation.

**L. Wetherill** (General Electric Company, Pittsfield, Mass.): This paper presents a broad view of the scope of the developmental testing which may be needed to establish the suitability of a line of bushings for modern service conditions. It is well that the magnitude and complexity of such an investigation should be appreciated since it also has a bearing on the circumstances encountered in revision of characteristics of existing bushings.

Quite a large number of tests are discussed, and it seems desirable that a way should be found to eliminate some of the tests which contribute little, if any, additional information. It is pleasing to note that Mr. Cole recommends discontinuance of the wet ten-second hold test. While this test has been used occasionally on circuit breaker bushings, it yields practically no additional information beyond that which is shown by the wet flashover test and the dry one-minute hold test. There certainly seems to be little justification for the retention of this test.

Mr. Cole refers to the one-minute hold test as being more severe than the dry flashover test. This doubtless results from the specific construction under consideration since it has been the writer's experience that, either with small bushings in which the dissipation of heat is easily accomplished without any great temperature rise, or in large bushings in which numerous oil ducts are disposed so as to thoroughly cool the main dielectric, it is possible to apply a one-minute hold voltage which is limited only by the tendency to flashover on the air end. Since the dry flashover test is corrected for atmospheric conditions, whereas the one-minute hold test is independent of atmospheric conditions, the relative severity of the two tests depends on atmospheric conditions. For standard atmospheric conditions the dry flashover test is more severe, but for low air density and humidity the one-minute hold test may, under extreme conditions, become more severe. However, as stated by Mr. Cole, the one-minute test is intended primarily for the purpose of verifying correct manufacture, and it would appear that for this purpose the one-minute test is preferable to the dry flashover since the voltage held is independent of atmospheric conditions.

The usefulness of the 60-cycle dry flashover test may well be questioned since the impulse flashover test is somewhat more severe. The impulse flashover test also has the advantage that it is more representative of the type of overvoltages which occur in service.

The fact that different designs have different characteristics is again illustrated by the 60-cycle endurance test in hot oil. It can be shown theoretically that the temperature rise produced by dielectric losses inside of a bushing having solid dielectric is proportional to the square of the applied voltage and is not affected by the thickness or configuration of the dielectric. The presence of condenser foils modifies this principle somewhat but does not alter the general principle that for low voltages the temperature rise is low and for high voltages the temperature rise is higher, even though the thickness of dielectric is increased to maintain the same stress intensity. As a result, it follows that on low-voltage bushings, there is no danger of a run-away thermal condition as long as suitable materials and thicknesses are utilized. On very high-voltage bushings with solid dielectric, the temperature rises are greater, and the possibility of run-away thermal condition must be considered. Even at very high voltages, if oil ducts are located so as to cool the major dielectric, there is no danger of a run-away thermal condition, and bushings of such design will demonstrate a dielectric strength on endurance test at high temperatures equal to or greater than that at low temperatures.

A similar distinction is found in the application of power factor and capacitance measurement to bushings of different construction. It has been our experience that on bushings which have no floating metal foils or which have floating metal foils with oil ducts between them, there is no tendency for the capacitance to vary more than the amount which is caused by the normal variation in the properties of available materials. Therefore, while we record power factor measurements of bushings, for the purpose of comparison with readings which may later be taken in service, we find that the capacitance readings are not useful in this connection.

It has been our experience that for bushings in excess of 25 kv the best possible radio noise characteristics can be obtained only by the use of liquid filling compounds which will have no tendency to form voids due to cooling or due to electrical discharges caused by overvoltages encountered in service. I believe that these advantageous features of liquid filling compounds are now being generally recognized.

It is satisfying in some ways to be able to measure the impulse puncture strength of a bushing, but we have found it preferable to measure this strength in terms of endurance rather than voltage. It has been our experience that standard bushings cannot be punctured on impulse since they will always flashover on the outside, even though totally immersed under oil. It also appears desirable that the impulse puncture strength should be verified with reference to its relation to the external flashover voltage. We have, therefore, undertaken to establish the impulse puncture strength by means of repeated flashover tests. Investigations with impulse flashover voltages of varying forms ranging from the full 1.5 x 40 microsecond wave to very steep waves rising at a rate of several thousand kilovolts per microsecond have indicated that the severest condition appears to result from the use of steep waves rising at approximately the rate of 1,000 kv per microsecond. We have made numerous endurance tests using this wave with which we expect a bushing to be good for approximately 1,000 applications at intervals of 30 seconds.

**V. M. Montsinger** (General Electric Company, Pittsfield, Mass.): Mr. Cole has presented a very complete paper giving the electrical characteristics of bushings. Unfortunately the paper emphasizes the use of gapped bushings as a protection to transformers against lightning.

There is one point in connection with the characteristics of a gapped bushing that should be mentioned. Unless the arcing length is appreciably reduced by the gaps, the benefits of the gaps in reducing the impulse flashovers disappear on steep wave flashovers when they are most needed. In fact, extremely steep-front waves will often flashover at some place other than on the gap electrode.

This, naturally, leads us to the question of why gaps were put on bushings in the first place. The principal reason was that when commercial impulse testing of transformers was set up a few years ago, it was required that the magnitude of the applied impulse wave be measured by flashing over the bushing. This required controlling the bushing flashover values by means of adjustable gaps. These gaps were provided primarily for this purpose and not as a protection to the transformer in service.

Now that impulse testing of transformers is to be made on a kilovolt basis, instead of on bushing flashover, there is no longer any necessity for the use of adjustable gaps on bushings during impulse tests. The principal objection to bushings is that gaps may give some operators the impression that they will protect the transformer under all conditions.

On account of the faster rise in impulse kilovolts of the volt-time curve of an air gap (as the time to flashover gets shorter), gaps give no positive protection to transformer windings against steep waves unless set much lower than that provided by standard gaps on bushings.

It is strongly recommended that if it is felt that a gap must be used for protection against overvoltage, it should be connected to the circuit a few feet away from the transformer bushing to prevent the possibility of a flashover damaging the bushing.

There is not much question but that some of the statements made in the paper will not clear up but will still further confuse the question of protecting transformers with gapped bushings. The statement "Co-ordination of bushing and winding becomes practical when a gap is used" might lead an operator who does not know the whole story to think that if a bushing has a gap on it with a standard spacing there is no need of providing any further protection. If hit with a direct stroke it is very doubtful if the transformer could stand it. All operators who are using gaps to protect transformers use spacings much lower than 44 inches for 138-kv circuits. One large operating company started with 20 to 22 inches for 110-kv service but later changed to 24 inches; another company changed from 20 or 22 inches to 11 inches.

Other well recognized and effective methods of protecting transformers as well as service, are available and these methods should be used instead of relying on gapped bushings which give only partial protection to the transformer and no protection to service.

It would have been much better if Mr. Cole's paper had pointed out the conditions under which gapped bushings give partial protection, rather than giving the impression that if the bushings are provided with gaps the transformer is co-ordinated which to many means that it needs no further protection.

**P. L. Bellaschi** (Westinghouse Electric and Manufacturing Company, Sharon, Pa.): The improvements in the present condenser bushing, discussed in Mr. Cole's paper, are the outcome of extensive work during the past several years. In view of the more exacting requirements fundamentals have been brought to bear on the various problems particularly where this approach was more conducive to practical results. One instance of this is the design for flashover to meet specified values and also means of readily controlling this important characteristic.

Standing back of this development are the extensive tests in the laboratory. Hundreds of repeated tests, both with long and very steep impulses have been applied to a bushing design or to bushings in combination with transformer windings. Of particular interest to operators is the experience in testing over $1^1/_2$ million kva of transformers equipped with condenser bushings. Further improvements in bushing design have been suggested through this experience but in particular it has been on this testing ground that ample proof has been given of the present condenser bushings design in fulfilling its specific impulse requirements.

The extent to which the development described by Mr. Cole has been pursued is illustrated in figure 1 of the paper. Here we have virtually a lightning stroke discharge across the bushing. The voltage applied rose at the rate of 3,000 kv per microsecond followed upon flashover by a current discharge of 90,000 amperes having a duration greater than 100 microseconds. While such severe tests may not be altogether a check on all possible service conditions to which a bushing may be subjected in the course of service, nevertheless, it is clearly an indication of the progress that has been made in the field of bushing design.

**F. J. Vogel** (Westinghouse Electric and Manufacturing Company, Sharon, Pa.): Mr. Cole's paper lists the electrical characteristics of bushings and shows the large number of tests necessary to show that a bushing is satisfactory for service. Most of these tests are design tests which are not feasible on each and every unit. Control tests and guaranteed tests can be reduced to relatively few. These latter tests can be made on the individual units.

It is of interest to go into the history of insulation co-ordination. Some years ago, statements were freely made that the higher voltage transformers as a whole were stronger against impulse voltages than line insulation, and that the windings in turn were stronger than the bushings. Experience was used as the evidence, and the surge generator had not been developed for use with transformers. Data of a reliable nature were not available for the common insulating materials.

The advent of the surge generator made it possible to check impulse strengths of materials and complete units, and it was found that experience was a poor teacher as shown by the results of the laboratory. In many cases, the strength of transformer windings was found to be lower than the strength of the bushing, and the bushing lower than the line insulation. It was felt that if the relationships between line insulation, bushing, and winding were specified when it was not known whether they could be obtained or not, they must be desirable and they should be obtained if possible. Careful investigation has showed that they could be obtained within reasonable limits, except in the cases of severe or direct strokes. The trend has been to abandon these desirable characteristics because they were found to be difficult to obtain generally. The acceptance of voltage values has led to a big reduction in the requirements and possibilities of a reduction in the impulse strength of equipment as now built.

There is one point which I would like to re-emphasize. That point is covered in Mr. Cole's paper, showing that a considerable degree of co-ordination has been obtained with bushings and insulation for the 138-kv insulation class. When the use of protective gaps was recommended, the gap length given was $38^1/_4$ inches. From figure 9, the full-wave value for negative waves for a $38^1/_4$-inch gap is about 700 kv, as high in voltage as the 44-inch gap for positive waves. It is understood that the negative-wave flashover of some types of bushing may be the same or less than the positive flashover. In this case, bushing flashovers might have occurred instead of protective gap flashovers due to insufficient margin between the protective gap and the bushing flashover. This should not have occurred with past designs of transformer condenser bushings due to the fact that the negative-wave flashover has been higher than the positive flashover.

The statement has been made that bushing flashovers invariably damage the porcelain. This is not always true. By the use of gaps properly arranged, the power arc can be largely directed away from the porcelain even though the gap parts are on the cap and flange. This can be demonstrated. Also, the initial flashover, either 60-cycle or impulse, can be made to clear the porcelain and not damage it. These features have not been emphasized, since it has been felt that bushing flashovers should be avoided. The use of a service gap, say $34^1/_2$ inches long for the 138-kv class, at the terminals of bushings should avoid bushing flashovers and provide a considerable measure of winding protection.

Where arresters are used, such a gap would only flashover in cases when the discharge current was excessive or the arrester was too far away from the transformer to supply protection for steep high surges.

Under these conditions, flashover is bound to occur somewhere, and the gap will locate it so that it will do the least damage and protect the transformer windings.

**H. L. Cole:** The subjects presented in the paper have resulted in some useful and interesting discussions, and the author appreciates the interest shown.

Mr. Pierce recommends that gap electrodes be away from the bushing and not integral with the bushing itself. If the gap is removed to a point where no damage can be done by flashover, it will probably be far enough away so that the bushing may be said to be not co-ordinated. Such a gap would be special for each transformer and the design would lose much of its simplicity and practicability.

Mr. Wetherill discusses the "endurance test" from the standpoint of type of bushing construction. Now there are a number of different types of bushing construction, all of which have been developed to a high degree of perfection. It was not the intention of the author to discuss differences between types of bushings, but it is important to note that the presence of condenser foils, as Mr. Wetherill describes the application of the condenser principle to a bushing, is what actually distributes the stresses uniformly throughout the dielectric, keeps the temperature at a low value, and makes the use of oil ducts to prevent overheating unnecessary.

It is not proposed that the bushing be used as a principal means of protection for the transformer. What is proposed, and what has been practiced for the past five years, is that a substantial amount of additional protection be obtained by making the bushing with impulse flashover characteristics so that it will have a flashover slightly under the transformer winding strength for as many types of waves as practicable.

Referring to Mr. Montsinger's discussion, the primary reason for controlling bushing flashovers was not for measurement purposes, but to give some winding protection. Originally the operators insisted that bushings have a lower impulse level than the windings. They did not require the use of gaps. Gaps were installed by the manufacturer to obtain either uniformity of results or the desired level. The bushing gapped or ungapped was demonstrated to give some protection to the transformer in service, and was not in itself a measuring device.

Even before commercial testing, there was a demand for co-ordinated bushings. Some engineers disagreed with the idea, saying that it was impractical. The demand persisted, and the writer tackled the problem of producing a bushing which would have as good co-ordination as possible. The present paper describes the progress made and the results obtained.

Transactions

Papers and Discussions Comprising Pages 35–82 of the 1939 Volume

# Co-ordination of Physics With Electrical Engineering

By J. M. BRYANT
MEMBER AIEE

THE early departments of electrical engineering in American universities were outgrowths of courses developed in physics. In most engineering colleges some member of the physics faculty offered application courses in physics for engineering students and after a few years these developed into a complete curriculum with a separate faculty for electrical engineering in parallel with the older civil and mechanical engineering curricula.

The early courses were mostly descriptive in nature with some emphasis on design of electrical machinery. The only text available was that of "Dynamo Electric Machinery," a two-volume text on d-c machinery by S. P. Thompson, an English author. The early American texts in a-c theory were inadequate, with very few proofs, and the minimum of mathematics. The early papers and texts of Doctor C. P. Steinmetz were the first to lay a proper foundation in mathematical development for advances in a-c theory. Practicing electrical engineers were not properly prepared in either physics or mathematics to understand these texts and Doctor Steinmetz adopted calculus methods for the solution of differential equations and series methods for solution of long transmission lines, so that his texts might be of real use to these engineers. To the early text on "Alternating Current Phenomena" he added others, including his well-known text on "Transient Electric Phenomena" and then one on "Electrical Engineering," a book adopted as an elementary text for students in some engineering colleges. In each of these texts, the solution of circuits by the use of the complex number was introduced and the machines were reduced to circuits for their solution. This was a revolution in method, since most previous authors had developed a new theory for each machine and the machine and the circuit did not fit together.

Many colleges were slow to adopt these newer mathematical methods of analysis partly from the inertia and poor preparation of the faculty and partly from the lack of proper emphasis along these lines in the fundamental fields of physics and mathematics. When students, trained in these new methods of analysis, were absorbed by the industry, and more emphasis was placed on fundamentals of analysis rather than on descriptive methods, a distinct gain was possible in the development of better designs for electrical devices and machines and the extension of the field was much accelerated. The rapid advance of electrical engineering in the past 25 years is due in a large measure to the ability of engineers to analyze the problems mathematically and to measure the quantities involved with exactness.

At the present time adequate texts are available in a-c theory for both undergraduate and graduate instruction of electrical-engineering students and as reference texts for practicing engineers. In these texts the authors have adopted mathematical proofs with application to modern machinery and transmission circuits. Much praise is due to the willingness of publishers to encourage better texts in this field when profit has not been their only motive.

In the field of communication the early texts were mostly descriptive of the equipment and circuits with little emphasis on calculation or of background physical principles. Development in research by physicists in the field of electrical discharges in gases and the development of the theory of electron emission have made possible the development of vacuum tubes which have revolutionized the whole field of wire communication and have brought forth the newer field of radio communication. The vacuum tube and improvements in transmission circuits have changed the entire field of transmission of speech and music over wires by introducing repeaters at frequent intervals along the line which with better circuit equalization have made long-distance wire-communication clearer and of higher fidelity than local communication was a comparatively few years ago. With the advance of radio from that of telegraphy to that of telephony, it has been possible to link all phones in one international system. The early courses in vacuum tubes and radio were developed in some universities in the department of physics and in others in electrical engineering.

The vacuum and gas-filled tubes have invaded the power field of electrical engineering and these new applications are rapidly expanding into the fields of circuit control and d-c transmission of power. The early carbon-filament vacuum incandescent lamp was displaced by others using tungsten filaments, at first having a vacuum and later by those filled with inert gases. These advances were brought about by research in the fundamental physical phenomena. Other developments along parallel lines have produced the numerous electric lamps using electrical discharges in gases and vapors at low and medium pressures. Further research by physicists in gas laws and electric discharges have laid a background for the study of lightning, for the X-ray tube, and for various new subdivisions of the atom, giving rise to new products and new technique in both physics and engineering.

The two fields of physics and electrical engineering are again becoming more closely allied, so that courses may be developed by teachers in either department and taken by students in both departments. At the University of Minnesota, courses in acoustics, in electronics, vacuum tubes, and communication, both wire and radio, are taught in electrical engineering while those in the fundamental gas laws and nuclear physics are taught in physics. These courses are taken as majors by graduate students in either department.

In the field of mathematics a similar

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# The Co-ordination of Mathematics and Physics With Electrical-Engineering Subjects

By WALTER A. CURRY
FELLOW AIEE

NO DEFENSIVE arguments are required to justify the need and desirability of co-ordination between mathematics, physics, and electrical-engineering subjects; such co-ordination must exist to some degree in every electrical-engineering curriculum and the essential objective of this symposium is to create a discussion of views and to reveal the instrumentalities whereby such co-ordination may be and is achieved.

Fundamentally, the initial objective of an engineering program of studies is to inculcate in the student an appreciation and grasp of that approach to the solution of problems which has been designated as the scientific method, represented by an ordered sequence consisting of observation, analysis, generalization, and application.

This method rests squarely upon the science of physics, which treats of matter and energy, and the science of mathematics, which sets up the philosophy and techniques whereby the quantitative relationships of physical laws and principles may be expressed, investigated, and evaluated. The student entering upon the course in physics, having previously prepared himself in mathematics, is therefore qualified to fuse the two fields in the combined relationship which is basic to the scientific method. Thus, in the Columbia program, the student has a year of mathematics before entering upon the course in general physics, and two years of mathematics and one year of physics before he reaches his first course in electrical engineering subjects.

Training the student, in his physics courses, to search for the fundamental principles upon which a statement of the problem may be formulated, to translate such statement into its mathematical equivalent, to solve this equivalent and to interpret the results so obtained, represents an invaluable educational process. Such training actually expresses co-ordination with subsequent engineering courses to the highest degree, since these courses will utilize the same principles in attacking problems presented by their subject matter.

Such co-ordination does not imply that there shall be no overlapping of subject matter; a student in the electrical-engineering subjects may be effectively "tuned" to new material if the instructor gives a brief résumé of the underlying physical laws, in spite of the fact that these are known to have been discussed in previous courses. This not only refreshes the student's memory, but re-emphasizes the alliance between the new applications and the earlier subject matter, problems in both of which are amenable to the same scientific method for their attack and solution.

To keep such résumé within reasonable limits, however, there must be effective co-ordination between the electrical-engineering subjects and physics. At Columbia, this is provided in part through informal and voluntary discussion between instructors in the two fields. It is accepted as part of their duty, that instructors in physics inform themselves specifically as to the knowledge of physics assumed in engineering courses by members of the engineering-school staff, and conversely, those giving instruction in the engineering school are charged with keeping definitely informed on the instruction in general physics. There are available in the electrical-engineering department detailed specifications of the subjects treated in general physics, which vitalized by interpretive discussion, provide those elements necessary to the efficient collaboration of the two fields.

Referring to the student in engineering, the objectives of these courses (in general physics), recently defined by a faculty committee, are as follows:

1. To give the student knowledge of the phenomena of matter and energy, and training in how they can be quantitatively analyzed and classified by measurement and theory, so that he may make use of this knowledge and training as a common basis of introduction for further study in various courses in engineering.

2. To give the student a knowledge of the interrelationships of the different branches of physics, and an understanding of the development of the science of physics, its direction of progress, and the developments that have not as yet proceeded to the point of engineering application.

Thus, the desired co-ordination between the physics courses and the engineering subjects which follow is recognized in the first objective, while the second is essential to the broad engineering program. It may be noted incidentally that only about 60 per cent of the groups which attend the general course in physics are headed for engineering; the course is taught as physics and is designed for all students who intend to

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co-operation has been experienced as with that of physics. In spite of the handicap of poorer preparation in mathematics of students entering our colleges, the mathematics departments of the universities have been able to prepare these students for their undergraduate work in calculus. By a co-ordination of this work with a greater application of mathematics in electrical-engineering courses during the junior and senior years, the student is now better prepared than formerly at the end of his senior year. The department of mathematics has also co-operated by offering courses in differential equations and advanced calculus, in operational analysis, vector analysis, functions of complex variables and matrices for graduate students in electrical engineering and physics to parallel new methods of analysis required by these students and by industry. Through the use of these fundamental methods electrical engineering has passed from an experimental to an exact science. The hope for future advances in the field of electrical engineering still lies in the application of mathematics and physics to the solution of new problems and the design of new equipment.

## Discussion

For discussion see page 43.

major in science, including those who will specialize in physics and those who will enter engineering.

The electrical-engineering subjects rely on the preceding work in physics to establish clear concepts and understanding of the fundamental laws and relationships governing elementary magnetic phenomena, electrostatics, and the laws of current flow in simple d-c circuits. Dimensional relationships and systems of units are important adjuncts. The subject of light, as discussed in the physics course, is planned to establish a sound basis for the subject of illuminating engineering in the subsequent electrical-engineering program, and similarly treatment of sound and wave motion, atomic physics, and the conduction of electricity through gases, form foundation elements for the subjects of communication and electronics. Knowledge of the laws of motion for rotating bodies, treated in physics and mechanics, is manifestly essential to the proper understanding of generator and motor performance discussed in subsequent electrical-engineering courses.

The co-ordination between electrical-engineering subjects and mathematics follows along lines similar to those relating to the work in physics. The earlier mathematics subjects (analytic geometry and the calculus) coming throughout the first and second years, provide a basic training which is essential to all fields of engineering. These subjects are given in the college and are taken by mixed groups, of which possibly 60 per cent are planning to enter engineering. The major objective of this two-year sequence of formal mathematics is the development in the student of an appreciation and clear understanding of the science which **is** mathematics, coupled with the attainment of a measure of skill and confidence in the application of this science to the solution of problems, many of which have their framework in the fields of mechanics and physics.

This two-year sequence is followed in the third year by a one-semester course in engineering mathematics which discusses such items as:

> Fourier series, line integrals, ordinary and partial differential equations, complex number operations, determinants, elliptic integrals, empirical equations, harmonic analysis, nomographs, probability, gamma and Bessel functions.

Naturally, with a content of this scope projected for a one-semester course, the student does not proceed to great depth in any one of the above items. The objective is rather to acquaint him with them, and to give him some indication of their application to practical problems, particularly in the field of electrical engineering. The subject of differential equations, however, touched upon in a preceding course in the calculus is, in this course, carried considerably further, about one-half of the time being devoted to this item.

This course was instituted at the request of the electrical-engineering department and its objective is "to equip the student with the mathematical mechanism commonly used in all branches of engineering, but pointed particularly toward electrical engineering." It represents a directed effort to advance the student from what may be termed the "minimum" type of educated man to the "superior" type, these types being defined as follows:

> The "minimum" type knows the important physical concepts and is fairly well aware of their function in engineering problems, but he is not very strong in the mathematical management of these physical concepts. His strength is intuitional and experimental. He may be a valuable man.
>
> The "superior" type has all that the minimum type has, but in addition he has learned with his concepts of physics, the mathematical formulation of them. This man has superior capacities for design and research.

The liaison between mathematics and the electrical-engineering subjects is provided by an "engineering-minded" member of the department of mathematics, Professor L. P. Siceloff, who conducts the course in engineering mathematics, and who is the author of the preceding definitions. This link is an effective one and through it there flows an easy interchange of suggestions and requirements which may arise from time to time.

The sequence in mathematics beginning with analytic geometry, continuing through calculus, and concluding with engineering mathematics, provides the necessary skill to enable the student to master the mathematical aspects of his subsequent work in electrical-engineering subjects.

Furthermore, these courses, jointly with those of physics, are directly utilized in the fourth year, by a two-semester course in electrical-engineering problems, the purpose of which is to give the student an indelible realization of the intimate relationship which exists between electrical engineering, mathematics, and physics.

The means chosen for accomplishing this objective is a series of very carefully constructed problems which are so designed that their solution demands clear analytical procedure, combined with a certain degree of resourcefulness and perspicacity, while at the same time the student is required to understand and explain fully the origin of the underlying fundamental ideas and their extension and application to the problem at hand.

In the lectures that accompany this course the student has pointed out to him the connection between the general fundamental idea and the engineering applications. The fundamental ideas are always expressed in their general mathematical form, often using mathematics not available to the student at the time the principle was originally introduced in physics. The student learns the application of mathematical processes to engineering problems and the significance of mathematical operations interpreted in terms of physical and engineering phenomena.

As has been indicated in the foregoing discussion of co-ordinating courses, an essential factor in such co-ordination resides in the establishment of close personal relationships between the instructors of the several departments concerned, enriched by a cordial spirit of co-operation and motivated by a high idealism in the objectives to be sought and attained. But co-ordination, once achieved, cannot be left to maintain itself. The inevitable and necessary revision which the subject matter of an engineering or science course undergoes as time brings new developments and viewpoints in those fields, demands that such co-ordination be re-examined at intervals to insure its continued existence. At Columbia, during the past several years, this has been accomplished through committees, with membership representative of the departments involved, including those of mathematics and physics. Such a committee is serving at the present time, and it is anticipated that similar committees will be appointed from time to time in the future.

In conclusion it may be said that there is an essential unity to all knowledge, and the student in electrical engineering will value and appreciate his early and later courses more highly if there is an efficient continuity throughout his schedule of studies. This will be accomplished if there exists a planned co-ordination of his three major fields, namely mathematics, physics, and electrical engineering.

## Discussion

For discussion see page 43.

# Mathematics and Physics in Engineering

By MICHEL G. MALTI
MEMBER AIEE

MANY definitions are given of an engineer. For the purpose of this discussion I would define an engineer as a scientist who uses physics and mathematics to promote the welfare of mankind. His use of physics and mathematics presupposes a thorough knowledge of them and demands that he be capable of:

(*a*) Reducing his engineering problems to fundamental physical facts.

(*b*) Expressing the physical facts in mathematical form.

(*c*) Deriving from the mathematical statement the desired mathematical result.

(*d*) Interpreting the mathematical result physically.

These points are so important that they justify further elucidation. Let us illustrate them through the familiar problem of determining the transient current in a series circuit, with resistance and inductance, which is suddenly subjected to a constant electromotive force:

(*a*) The physical facts here involved are that the applied electromotive force is consumed in drops through the resistance and inductance.

(*b*) The mathematical expression of the physical facts is:

$$E = ri + Ldi/dt$$

(*c*) The derivation of the mathematical result consists in solving this differential equation and obtaining

$$i = (E/R) + K\epsilon^{-Rt/L}$$

(*d*) The interpretation of this result is that the current may be anything depending upon $K$. Hence we resort to the physics of the problem and assert that the current is zero at the instant $t = 0$ when the electromotive force is impressed. This gives $K = -E/R$ and hence the current for this particular initial condition is:

$$i = (E/R)(1 - \epsilon^{-Rt/L})$$

I have used this simple illustration to show the four processes involved in all engineering problems. The degree of ease or difficulty of one or the other of these processes varies with the nature of the problem. But each process exists in every engineering problem no matter how difficult or easy it may be.

Now it so happens that part *c* (the actual derivation of mathematical results) is something that an engineer need not master because he can always resort to the mathematician for the performance of this task. But every engineer should be a master of parts *a*, *b*, and *d* because neither the physicist nor the mathematician can be of assistance to him in this matter.

I doubt if there exists any disagreement among engineers about these statements. We also admit that the majority of engineers lack these essentials otherwise we would not be holding this symposium. We therefore conclude that something is wrong either in our teaching of physics and mathematics or in the proper co-ordination of these subjects with engineering courses or in both.

All these are facts which we agree upon. What we do disagree upon are the real causes of this condition and the remedies to be adopted. I do hope that when this symposium is ended we shall have attained a clearer insight into the real causes of the trouble and shall have adopted a course of action which constitutes a fundamental and effective remedy.

I shall now endeavor to give some of the causes and suggested remedies as I have collected them through talks with educators, students, and engineers and through personal observation and experience. This will then be succeeded by a critical analysis of them and a suggested solution of the problem.

(*a*) *Incompetence of Mathematics and Physics Teachers.* Some educators trace our woes to the teachers of mathematics and physics. They assert that these teachers do not understand the point of view of the engineer and are, therefore, unable to teach him these subjects. Both mathematicians and physicists are prone to emphasize facts which are essential to them but which are utterly useless in engineering applications. Furthermore physicists and mathematicians do not know engineering problems. Hence they are not capable of discerning what is and what is not essential to engineering. Obviously the remedy here consists in having mathematics and physics taught to engineers by engineers.

(*b*) *Lack of Co-operation.* Another group agrees that the viewpoint of the engineer should be stressed in both mathematics and physics courses but are less antagonistic to teachers of mathematics and physics. They are inclined to take a little of the blame upon themselves and ascribe the trouble to lack of proper co-operation between teachers of engineering on the one hand and teachers of mathematics and physics on the other. Some of the remedies here suggested include:

1. Frequent conferences between faculty members with a view of co-ordinating efforts.
2. Actually supplying the departments of mathematics and physics with typical engineering problems which these departments could use for illustrative purposes.
3. Telling the teachers of mathematics and physics what is and what is not essential in engineering and requesting that only essential facts be stressed in teaching physics and mathematics to engineers.

(*c*) *Lack of Time.* A third group blames neither the teachers of engineering nor the teachers of physics and mathematics. They assert that competence and co-operation exist to as high a degree as may be expected. Time or rather the lack of it is the cause of our trouble. Indeed the engineering curriculum is so crowded and the student is so rushed with his courses that there exists no time to stress the mathematical and physical aspects of engineering. To train an engineer to correlate physics, mathematics, and engineering is truly a time-consuming and a very exacting task. Moreover since time cannot be conserved through the elimination or revision of engineering courses there appears three possible remedies.

1. Extension of the engineering course to more than four years.
2. Offering graduate courses in colleges to men who expect to engage in strictly engineering work.
3. Delegating, to industry, the responsibility of training engineers through advanced courses.

(*d*) *Incompetence of Engineering Teachers.* A very small fourth group is willing to shoulder the whole blame and admit that, sometimes, the cause of the trouble can be traced to the very teachers of engineering themselves. This group argues that there is a golden opportunity for engineering teachers to correlate mathematics and physics in their own courses. Such teachers should stress the physical laws and mathematical relations which form the bases of engineering applications in order that the student may form a concrete picture of how physics and mathe-

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matics are used by the engineer. If the contention of this group is true, then the remedy obviously consists in having, on our engineering faculties, men who combine a good engineering training with a thorough and comprehensive knowledge of mathematics and physics. Such men should, moreover, possess the gift of conveying their thoughts in a logical, clear, and comprehensive manner to their students. The task of the engineering teachers thus becomes most exacting and their selection requires the most careful scrutiny of college presidents, deans, and department heads.

It would appear that elements of truth exist in the contentions of all four groups. Let us, however, examine them a little more critically.

(*a*) While it is desirable that physicists and mathematicians do appreciate the engineer's point of view, such appreciation is of precious little help to the freshman and sophomore student who has no inkling of what engineering is! To tell a freshman that the laws of gases are used in connection with engines, turbines, and air-conditioning machines might attract his interest. But it means little or nothing to him because he knows nothing about the design or operating characteristics of such machines. Nor would it profit the sophomore much when he is advised that Faraday's law of induction is the basis of the design and operation of all electric machines because he knows little if anything about electric machines. It still means less to an immature student to be told that a linear differential equation of the first order with constant coefficients represents a series circuit with $R$ and $L$ or with $R$ and $C$ because such a circuit is just as mysterious to him as the differential equation itself. Indeed, to an immature freshman and sophomore, engineering is more strange than the physics and mathematics he studies. It would appear, therefore, that the time to show the application of physics and mathematics to engineering problems is not during the freshman and sophomore years but during the junior and senior years when the student is actually engaged in studying engineering. It thus becomes incumbent on the *teachers of engineering* rather than those of physics and mathematics to demonstrate and elucidate the application of these basic sciences to engineering problems.

(*b*) There is much to be gained from conferences between teachers of engineering and of the basic sciences provided these conferences are well planned and well directed and provided that a sincere effort is exerted by all to see one another's point of view. Such conferences should have for their object:

1. The understanding, by mathematicians and physicists, of the processes involved in the solution of engineering problems as outlined earlier in this discussion.
2. The understanding by engineers of the processes of analysis which a mathematician utilizes in formulating and solving his problem and the physicist uses in making his discoveries of physical laws and in correlating physical phenomena.

To my mind it would be disastrous to dictate to a physicist or mathematician what he should or should not teach engineering students or how he should present the subject matter. To dictate the contents of a course would emphasize the utilitarian and exclude the interest aspect of education. To dictate methods of presentation would rob the student of the mental enrichment which comes out of studying several modes of attack and establish in his mind narrow tracks and processes of reasoning which might or might not prove helpful in attacking his future problems.

(*c*) The problem of lack of time is a serious one and I would welcome the extension of the engineering course to more than four years provided all educational institutions throughout the country agree to do so. But I insist that, even in four years, engineering colleges can do better by their students if they require less substitution in formulas, less graph plotting, less slide-rule work, and more brain work. In fact, even if the engineering course is extended to five or six years I would recommend that the present mode of running some courses, with the idea of consuming the student's time rather than exercising his brain, be abandoned, and the courses be so changed that time is spent in thinking rather than in slide-rule pushing and graph plotting.

(*d*) It is obvious that all these recommendations lead to one effective solution—the improvement of engineering faculties. The remedy lies in having engineering teachers who are not only well-trained engineers but who are also good mathematicians and physicists. The time is past when a knowledge of algebra and of Ohm's and Faraday's laws were all the tools that an electrical engineer needed. The time is gone when an engineer jokingly remarks that the place of an integral sign is on the violin. Such mathematics as functions of complex variables, functions of real variables, theory of sets, theory of groups, calculus of variation, ordinary and partial differential equations, advanced algebra (tensors, etc.), and vector analysis are commonly used in the solution of engineering problems. As to physics, the electron theory comprising conduction of electricity through gases, electron emission, photoelectricity, X-rays, etc., and such subjects as quantum mechanics, light, heat, and others are just as essential to the electrical engineer of today as Ohm's law and Faraday's law of electromagnetic induction were to the pioneer engineer. Engineering teachers should realize these facts and prepare themselves to meet present-day demands.

The following evolutionary process may be suggested to improve our present faculties in the larger universities:

(*a*) Have all graduate students in engineering who are working for a degree of doctor of philosophy take mathematics and physics as minors.

(*b*) Appoint assistants from among these graduate students and keep records of their scholarship and teaching ability, as well as their character and personality.

(*c*) Select from among the assistants those who show most promise and encourage them to specialize along various lines. These men, upon receiving their degree of doctor of philosophy should be appointed as instructors.

(*d*) Make research accomplishments and teaching ability necessary (although not sufficient) conditions for promotion.

(*e*) Have the faculty keep in touch with industry in order to follow the developments of the time.

If this policy is adopted by our leading educational institutions every first-class college would, within a brief period of perhaps ten years, have an excellent faculty and the problem we are discussing in this symposium would become of minor importance!

But I hear the voice of the personnel man reminding me that over 80 per cent of our graduates finally end in sales offices or in executive positions with very little possibility of their ever using physics, mathematics, or even engineering and that the remaining 20 per cent or perhaps even 10 per cent who actually do engineering work are trained in special industrial courses! So why all this fuss about knowledge of mathematics and physics and their correlation with engineering subjects? To the personnel man and his ilk I say:

The purpose of all education is mental training. College courses are but vehicles to attain this end. In these courses facts are learned and quickly forgotten. What the student retains are the mental processes which he unwittingly acquired while he pursued these courses. If one's mind is fertile and receptive and his tutors are alert, enthusiastic, and competent, then one's mentality should be so developed, when he completes his college training, that he can:

(*a*) Study independently of teachers.
(*b*) Synthesize isolated facts.
(*c*) Generalize from fundamentals.
(*d*) View facts objectively.
(*e*) Visualize things.
(*f*) Do original work.

I know of no mental faculties that are more essential to an engineer than the above. This holds true whether he be a salesman, a designer, an executive, a teacher, or a gang boss. Moreover I know of no courses which develop these mental faculties more intensively and more sharply than mathematics, physics, and engineering.

## Discussion

For discussion see page 43.

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# Courses to Develop Facility in the Use of Mathematics and Physics in the Solution of Engineering Problems

By B. R. TEARE, JR.
MEMBER AIEE

IN RECENT years engineers and teachers have recognized[1,2] that many graduates lack facility in the use of mathematics and physics in the solution of engineering problems. Appearing to know the principles of science that underlie engineering, the young graduates frequently cannot apply them correctly in new situations. It is evident that the development of the requisite facility depends upon first, mastery of the basic sciences and second, adequate training in their application. Thus, there is need for two different kinds of co-ordination of mathematics and physics with electrical engineering: co-ordination of the departmental teaching activities for most effective instruction, and co-ordination of the subject matter in the student's mind for most effective use.

Co-ordination of the first kind may be achieved by close co-operation between the faculties of the departments concerned. Various ways of obtaining the co-operation are available.[3,4] To cite an example, there is a committee for this purpose at Yale University, composed of representatives from the mathematics, physics, mechanics, and various engineering departments. Committee meetings, held frequently, provide opportunities for the interchange of points of view and for suggesting, where desirable, a redistribution of the emphasis placed on particular topics in the various courses. Although the first type of co-ordination is recognized as essential, it does not remove the necessity for the other type.

The student has been well instructed in the basic sciences but too often has not received adequate training and practice in their co-ordinated use. Such training and practice can be given by means of a course organized for this purpose. For example, the advanced course in engineering of the General Electric Company,[2] working with a selected group of graduates in industry, has for one of its objectives the development of facility in the application of mathematics and physics to the solution of engineering problems, and is notably successful in attaining this end. It is the purpose in what follows to discuss a program to give such training to the student before he leaves college.

For the last six years the electrical engineering department at Yale has given junior and senior courses of three hours each comprising a unified two-year program of this type, and also a parallel one-year graduate course. The subject matter, and manner of conducting the courses are selected for the most effective co-ordination of the basic sciences with electrical engineering. The introduction of new topics is subsidiary to the development of a thorough understanding of the old.

Since the aim is to develop facility in the use of mathematics and physics in the solution of engineering problems, naturally the chief emphasis is on problem solving, both in class discussions and in assignments. As far as possible, problems are selected which present new situations, where the solutions are to be obtained not by substitution in handbook formulas but by the application of such fundamental principles as, for instance, Newton's laws of motion, or Fourier's law of heat conduction. Two examples, representative of the more difficult assignments, are given for illustration.

> 1. It is proposed to support a motor by means of an elastic mounting in order to reduce vibrations that are transmitted through the mounting to the supporting foundation. The vibrations originate in centrifugal forces due to mechanical unbalance, or in pulsating electromagnetic forces, and occur at definite frequencies. The effectiveness of the mounting is to be measured by a quantity called transmissibility, which for vibrations of a given frequency is the ratio of the steady-state amplitude of the force transmitted to the base through an elastic mounting to that transmitted through a rigid mounting.
>
> For an elastic mounting, which has damping, and considering only vertical vibrations,
>
> (*a*) Determine the transmissibility in terms of frequency and system constants.
>
> (*b*) Illustrate the result by sketched curves of transmissibility as a function of vibration frequency for various values of damping.
>
> (*c*) Discuss the value of an elastic mounting which has little damping, if the vibration frequency is about half the natural frequency of the vertical vibrations of the motor on its mounting.
>
> 2. In a proposed thermocouple ammeter, the current to be measured is passed through a thin straight metal strip supported between two massive terminal blocks. One junction of a thermocouple is placed at the midpoint of the metal strip, the other junction on one terminal block, but electrically insulated from it. The thermocouple is connected to a galvanometer.
>
> (*a*) Express the temperature difference between junctions in terms of the voltage drop between terminal blocks, dimensions, and thermal constants.
>
> (*b*) What length of heating element will give the largest temperature difference between junctions for a given power loss?
>
> (*c*) What are the disadvantages of this type of meter?

That these problems are of practical engineering interest is shown by the fact that they were presented in technical papers appearing during the last five years.[5,6] The students were not given the

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1. For all numbered references, see list at end of paper.

references until after they had obtained solutions.

In all the assignments, except the relatively few exercises employed for drill in new topics, the student is given an unfamiliar situation in which simplifying assumptions must usually be made in order to obtain a solution, and in which as far as possible he must select the variables with which to work. The required physical principles and mathematical techniques, however, will have been covered in class work and perhaps in other assignments.

Through the duration of the courses much emphasis is placed on the orderly arrangement of thought processes in the solution of problems. The arrangement which is applicable to problems of the deductive type, has been discussed elsewhere[1] and may be summarized in the following steps:

I. Stating the problem and specifying the desired result. The student is to use his own words and illustrate with sketches where possible.

II. Formulating a plan of solution, which includes

(*a*) Selecting a principle to be applied;

(*b*) Making whatever simplifying assumptions may be necessary;

(*c*) Planning the treatment as far as it may be foreseen.

III. Stating in precise English the implication of the chosen principle in the particular problem.

IV. Translating the statement of III into mathematical form which includes

(*a*) Specifying notation;

(*b*) Selecting co-ordinates;

(*c*) Writing III as an equation.

V. Solving IV*c*, which usually includes introducing additional relations, and perhaps also additional simplifying assumptions. Should a solution of IV*c* be impossible, a fresh start applying a new principle is to be made.

VI. Testing the solution

(*a*) For dimensional homogeneity;

(*b*) With extreme values assigned to variables;

(*c*) For reasonableness in the light of experience;

(*d*) For possible effect of the simplifying assumptions.

While this formulation may appear inflexible, it is so only as regards the inclusion of all the steps and in order. Many problems require the use of more than one principle; in other words the desired solution can be considered to result from the simultaneous application of a number of principles. However, this organization of thought processes implies that but one is to be chosen to start the solution, and there may be some latitude in the choice. Moreover, there may be another kind of selection to make since some physical laws are merely different expressions of the same fundamental truth. Any one of these may be used in a given case, although often a particular one leads to a more direct solution.

The principles which are discussed in the courses and used in the solution of problems comprise the general fundamental laws of mechanics, heat transmission, electrostatics, magnetostatics, and circuit theory, such as Newton's laws of motion, conservation of energy and of momentum, the principle of superposition, Fourier's law of heat conduction, Newton's law of cooling, Coulomb's and Gauss's laws for electric and magnetic fields, Ampere's and Kirchoff's laws, Faraday's electromotive-force law, and the constant-linkage theorem, to name but a few. The student has encountered most of these previously in mechanics and physics and indeed can usually state them with fair accuracy. He is expected, however, to develop such understanding of the laws, their range of application, and the physical quantities they relate, that he can select appropriate ones for the solution of a new problem.

Considerable time is devoted to the review and use of familiar mathematics and to the treatment of more advanced techniques, including the solution of second-order linear differential equations with constant coefficients, elementary vector analysis, Fourier series, symmetrical components, and dimensional analysis. These new topics are introduced in the solution of particular problems and later generalized.

The analogous behavior of electric circuits, mechanical systems, and heat conduction systems, expressed in exactly similar equations, provides a natural unification of portions of mathematics and physics with engineering, and is of great assistance in augmenting the student's understanding. Likewise the broad analogy among the space fields of electrostatics, magnetostatics, gravitation, thermal and electric conduction, and fluid flow described by similar vector equations and identical field maps, furnishes another natural means of integrating the subject matter. A consideration of the points of difference between analogous systems is as helpful in building up understanding as the mention of matters of similarity.

Classes are conducted as seminars, where each student contributes to the discussion, rather than by formal lectures. Supplementary laboratory exercises are given in the junior year, in which the student is required first to solve a given problem theoretically and then verify his result experimentally. In the senior year the work culminates in projects, individual development problems usually requiring work in the laboratory, and short enough so that two or three can be completed. Such projects, for example, may be the combined theoretical and experimental study of dynamic braking of d-c machines, or of the performance of thyratron inverters. About a quarter of the senior course is devoted to this kind of activity.

The relation of these two undergraduate courses to the program as a whole has been described elsewhere.[1] They are required of all the undergraduates in electrical engineering, and each course is allotted one-fifth of a year's time. They are co-ordinated with each other and with the other electrical engineering courses to unify the program as a whole. At the end of the senior year the student's grasp of the entire technical portion of his work in all four years is tested in a searching departmental, or comprehensive, examination.

In conclusion, the courses to develop facility in the use of mathematics and physics in engineering problems have these essential features:

(*a*) Training in an orderly thought process;

(*b*) Integration of the student's knowledge of the basic sciences;

(*c*) Extensive practice in the solution of actual engineering problems.

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## Discussion

For discussion see page 43.

# Co-ordination of Mathematics and Physics With Electrical-Engineering Subjects

By THEODORE H. MORGAN
MEMBER AIEE

IN RECENT years all branches of engineering have experienced rapid growth and progress. Technological advancement has been accompanied by an increasing realization of the breadth and scope of the profession. College curricula have been altered and adjusted in attempts to meet changing conditions. We have been forced to realize that the solution of our educational problems is not to be found in an increased amount of work or in adding further courses to already overcrowded curricula, but rather in more complete co-ordination and unification within the programs themselves. Due to the manner in which the engineering curricula have been built up through the years, new subjects being added from time to time as was found necessary, we are in danger of thinking of a curriculum as being composed of separate blocks, i.e., so much mathematics, so much physics, chemistry, and so forth. Our problem is to break down the well-defined boundaries of these blocks so that they will be combined to form a unified and coherent whole. We might compare the curriculum to a painting for which the artist carefully chooses a number of colors which are not used separately in blocks, but are harmoniously blended and intermingled in a complete picture.

Let us look at mathematics and physics. When taught only as the science of order, giving quantitative and magnitudinal relations of pure numbers, mathematics loses much of its value to the engineer. The student should become familiar with this subject as providing an indispensable and powerful tool of the profession. In teaching mathematics, as the beauty and mystery of pure numbers is unfolded to his mind, the student should learn at the same time the practical value of the subject in dealing with physical relations. This can best be accomplished through a high degree of co-ordination between the courses in mathematics and those dealing with the physical sciences, of which the subject of physics is perhaps the best example. The co-ordination that I have in mind requires close relationship between departments. The instructor in mathematics must be thoroughly conversant with the course in physics, and vice versa, so that the work is carried forward simultaneously—the mathematician applying the laws of physics in his mathematical developments at the same time that the physicist is building in the student's mind an understanding of a fundamental law which is being given definite form and expression in mathematical symbols. The learning of general mathematical principles, manipulations, and technique, should go hand in hand with their use and application. The student would thus realize that in mathematics he has a powerful and precise instrument which can be used with perfect exactitude to solve physical problems. As this usefulness became increasingly evident both mathematics and physics would take on new interest and importance in his mind.

The subject of physics by its very nature covers a greater field than any other course in the curriculum. It is the foundation for all engineering courses, which are largely specialties in physics having important practical value. It thus becomes essential that the engineering student form proper habits of thought in such matters. His introduction to principles which are new to him should be accomplished in such a way as to appeal to his common sense and intuition. In contrast to the memorization of stated formulas the student should be required to perform for himself the much more important and difficult task of expressing physical laws and facts in mathematical terms. Once this is accomplished the mathematical developments and manipulations would follow simply and easily. The acquisition of fundamental knowledge would go hand in hand with the development of scientific analysis, requiring deep-seated understanding and proper habits of thinking and reasoning, and the student would recognize physics and mathematics as belonging to fundamental science, together forming the foundation of engineering.

Furthermore, the student who elects an engineering course has a natural interest in and zeal for his chosen field of work. The proposed plan would capitalize upon this enthusiasm by permitting the student to start his college course with work which he would recognize as possessing the essential properties of engineering, instead of feeling that he must wait for about two years before starting work of this character. Not only would his interest be greatly enhanced thereby but aptitudes would be discovered at an earlier date.

Under the present plan a student may come to graduation without full appreciation of the unity that exists throughout all of his work. Relationship between courses, while an interesting speculation, may never be fully understood. Individual courses are frequently viewed as something which must be passed and thus "gotten out of the way" before more advanced work can be undertaken.

The question might be raised as to whether certain important educational losses would not be sustained through the introduction of such a plan. There is no doubt that the study of mathematics and physics as pure science can have great value to the engineering student. The very nature of these subjects gives the student a broad philosophy and viewpoint with respect to science which it is difficult to develop in engineering courses because of their limitations. These values need not be lost but might even be increased by proper teaching of the co-ordinated work. To accomplish this, great care should be taken to insure that the student is made to fully appreciate the *complete unity* and the *simple beauty* that exists in natural law. Co-ordination of science subjects would give a better opportunity to develop a more complete understanding of the underlying correlations between the various elements of science. Respect and esteem for the unity, beauty, and truth in natural law would be enhanced by a fuller and deeper appreciation of the interrelationships and parallelisms which constantly present themselves.

Considering the co-ordination of mathematics and physics as the first step, the second step in our proposed program would be to unify and co-ordinate all electrical-engineering courses themselves. These subjects can all be brought together into one closely woven whole and developed as one broad course from the initial elementary work to the time of graduation. Laboratory and classroom courses should not exist separately, but each division of the work should receive

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investigation in the laboratory at the same time it is being discussed in the classroom. Thus theory and practical understanding would be developed together in a logical manner. Comprehensive knowledge and understanding would thus be obtained as a result of thorough investigation from different points of view.

The third and final step required to complete our program of unification would be the bringing together of the co-ordinated work in mathematics and physics with similarly organized work in electrical engineering. The problem here is to make the student realize that he has not completed a course which can be left behind and forgotten, but rather that he is going forward into more advanced work which is a continuation of what has gone before requiring constant use of the principles he has learned. In order to carry this out with smoothness and harmony, instructors in each department should be thoroughly familiar with that portion of the work of the other department which lies close to the transition point. Even with the best co-operative spirit on the part of the faculties concerned it will take considerable time to plan such a program and effectually put it into operation. Many difficulties will exist in any institution, but no worth-while accomplishment in education is easy of attainment.

At Worcester Polytechnic Institute the previously outlined general plan is well underway for the electrical-engineering curriculum. The order in which the separate steps were undertaken has been somewhat different from that outlined herein. Our initial effort was devoted to co-ordinating thoroughly all of the undergraduate work given by the electrical-engineering department. The curriculum was completely revised four years ago in order that this work might go forward and the present senior class is the first to graduate under the new plan. There is unanimous agreement on the part of the department staff that the results show marked improvement in the students' comprehensive knowledge and general understanding.

Our second step is to co-ordinate the work of the physics and electrical-engineering departments. The problem has received much discussion and is being attacked with a fine spirit. Small groups composed of members of both departments are now working together on the many details. It is realized that if lasting good is to be accomplished much care and attention must be given to every step. In order to help the student appreciate the union between physics and electrical engineering the staff of the latter department will stress the importance of work in physics by frequently referring back to principles previously covered in physics courses, thus emphasizing the continuity. Similarly, members of the physics department will attempt further to awaken student interest by pointing out practical applications of the principles taught by them.

The objection may be raised that the amount of ground covered in a co-ordinated curriculum of this nature necessarily would be less. The answer is that the student's knowledge, understanding, and power of analysis would be increased. The measure of a college education never was, and never should be, the number of items covered in the separate courses of the curriculum. Many years ago the college with which I am associated adopted as a motto "Pauca Fideliter"—a few things faithfully. As we look forward to greater accomplishment in engineering education we must break down the barriers between the individual subjects so that the unity which exists so abundantly in nature shall permeate the separate parts and consolidate them into one complete whole.

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## Discussion

**Royal W. Sorensen** (California Institute of Technology, Pasadena): This symposium comprising the several papers has, indeed, been interesting and very instructive. It is so complete as to leave little that may be said in the way of conclusions; for, after all, all of us assembled here are not only engineers, but are professional teachers. We have, or should have, attained this professional standing by virtue of being men who can discern and devise our own ways of finding and overcoming students' impedimenta to learning. I don't agree with the ideas which some have presented, that the best teaching is always the one which makes learning easy. In fact the lifetime work of an engineer is that of doing new things. Invariably starting friction is greater than running friction. A future engineer should, therefore, while he is a student, learn to avoid being dismayed by heavy starting friction: that is he should, at least a part of the time, have the stimulus of unraveling problems in his own way even though that may be a very difficult one. Naturally as a teacher I try my best to present subject matter in such a way as to be readily understood; but I am not overly exercised if the students find the explanations difficult to understand. Will not these men, as they go out into practice after graduation, often be placed in the position of having to take instruction from men difficult to understand? And is it not a part of their business as students to learn how to interpret difficult and sometimes befogged instructions?

Reference has been made to poor instruction in high schools in science and mathematics. I am of the opinion that the present high-school graduates who enter our engineering schools with good entrance requirements, are today better prepared in science and mathematics than was the case a score of years back. Are we not prone to judge preparation by what we require rather than by actual standards of today as compared to those which prevailed a generation ago?

The California Institute of Technology has for several years recognized the expanding scope of engineering and has included a large amount of humanities in its courses. This fact combined with the expanding field of engineering technique has made it seem wise to grant for four years work the degree of bachelor of science in engineering, rather than specifying a particular branch of engineering. At the present time, by doing an additional year of work, our students may obtain the degree, master of science in some special branch of engineering, such as electrical, mechanical, or civil. Our meteorology and aeronautics departments, however, have deviated from this plan, and at the end of the fifth year are granting the degree, bachelor of science in aeronautical engineering or in meteorology as the case may be. My years of teaching experience have led me to look upon the four-year engineering courses as dual-purpose courses—the major purpose, perhaps, being that of a general education rather than a professional education, the professional education to be obtained by added years. With this thought in mind I do not advocate extending what may be known as the regular engineering courses to five-year or six-year courses, but I rather think it better to have our present terminal, four-year courses and add thereto such work as seems desirable for engineering preparation. Undoubtedly this means that an increasing number of men will spend at least five and preferably more than five years in college work in preparation for an engineering career. Such a program may introduce a dangerous situation if we encourage men to go on beyond the fifth year for a doctorate degree and use for courses leading to the doctorate degree, simply additional technical work of the type which has been given in our undergraduate courses. Men selected and encouraged to go on for doctorate degree courses should be limited to men who have outstanding analytical ability and who can without difficulty master advanced courses in mathematics and physics. In fact a large part of the graduate work leading to a doctorate degree for engineers should, in my opinion, be work done under the instruction of our ablest mathematicians and physicists.

My own experience with younger teachers, in fact even with men pursuing graduate work, used as teachers, has been most excellent. By carefully selecting the men who are to do the teaching and introducing them to the work first through laboratory courses and then in the classroom, we find the results equal to and frequently better than the results sometimes obtained by older teachers. This is no doubt due to the great enthusiasm of the young men who wish to try teaching, coupled with their recent contact as young undergraduates with the problems as they appear to the undergraduate.

Returning to the undergraduate courses, I question very much the advisability of including in the first four years of work, courses in transients, long transmission lines, and higher mathematics courses, because I think, for the large group of students, the first four years of work can best be spent in acquiring training in the simple fundamentals of science and engineering plus a considerable amount of general cultural education including such subjects as English, public speaking, history, economics, geology, etc. This thought, I suspect, agrees with Professor Malti, who suggests that we have all graduate students working for a doctorate degree take mathematics and physics as minors. With this I agree, except that the minor should comprise a large part of the graduate students' course work. Professor Malti seems to recommend the appointment of men who have just received their doctorate degrees as instructors. I think it would be much better to have such men enter industry for several years before being selected as instructors. Malti's comments regarding ability to do research as a prerequisite to teach, and regarding having the faculty keep in touch with industry are pertinent.

**E. M. Strong** (Cornell University, Ithaca, N. Y.): For something over ten years I have met nearly all of the students in engineering at Cornell as they come fresh from mathematics and physics to begin their study of electrical fundamentals in the sophomore or junior years. The place and nature of mathematics and physics in the engineering curriculum continuously interests me and I am appreciative of the cross section of current thought provided by this symposium.

I do not believe that we need here to sell the idea that mathematics and physics have in the electrical curriculum a place which is both important and steadily growing. Anyone really interested in the symposium is alive enough to be well aware of this. What he wants to know is "How can the faculty and curriculum best function to accomplish the admitted objective?"

I am surprised that no one has mentioned the economic factor in the situation because with few exceptions it is a most potent element in the whole program. Possibly there is something in the local atmosphere here which taboos recognition of economic restrictions. There are several angles to the economic problem. Let me mention two of outstanding importance:

1. The use of instructorships to subsidize graduate study and research.
2. Insufficient supervised computation.

In physics and mathematics particularly we find too many young men holding instructorships who have no interest in teaching except as it alleviates the immediate financial stress during their graduate study. Sometimes they seriously lack essential qualifications for teaching and especially for the teaching of the less mature student in the freshman and sophomore years who consequently functions as the "guinea pig" or the "goat" for these "instructors." Students during these years, more than at any time later, need the best *teaching* talent on the faculty. However good the curriculum and however good the administration it can produce results only in so far as the personnel which ultimately and *directly* contacts the student is competent not only in technical knowledge but also in ability to impart that knowledge and to inspire enthusiasm in the student. No man can do this except that he be genuinely interested in the student—he cannot do it if his mind is filled with graduate study or research to the exclusion of all else in the mad scramble for a degree by June 1.

The problem is largely an *economic* one for faculty and graduate student alike. I have no solution to offer.

Returning now to item number 2 (insufficient supervised computation). Engineering faculties are confronted with an increasing difficulty in obtaining from the public schools of the country any dependable foundation in mathematics—let alone physics or chemistry or habits of study and conduct. In college the departments of mathematics and physics lack facilities for building up the student in these deficiencies. One of the most successful methods employed in engineering instruction is the computing period which provides for the student a time and place to develop what we call engineering habits in the approach to problems and their solution—not only time and place but the sympathetic supervision which makes for more efficient work in the earlier years, in particular, than can be found in home study alone.

The problem is primarily an *economic* one to provide the required facilities of staff and room.

There is one other phase of the general problem about which I am moved to comment. I am fully in sympathy with any of the true co-operative movements which some of the authors have outlined for us. However, there are two kinds of "co-operation." One of these is not found defined under the word itself in Webster but is formally defined under "coercion." Engineering says to physics: "Your work isn't giving our students the foundation we need—will you co-operate in a revision?" "Yes, of course we'll co-operate." "Well, here's what we want—so and so and thus." "But I can't teach that, it doesn't do justice to physics." "Well, if you don't want to co-operate, we'll give it ourselves." Whether this work is then taught in engineering or in physics the result is deplorable.

Engineering does not go to English and dictate that only technical and scientific English be taught—nor to history for exclusively technical or scientific history. For the most part it hasn't had the face to go to language and insist on technical German or French, exclusively. If and when engineering in a university cannot co-operate with the rest of the university it might as well set up by itself as a technical school because any university affiliation is then not only unprofitable but possibly detrimental to its functioning.

I quite agree with Doctor Malti that these university departments of mathematics and physics must not be "bulldozed" into teaching their work according to rigorous engineering specifications. Let them have something of a cultural as well as the strict utilitarian purposes. Let them be supplemented or complemented by work in engineering, possibly concurrent in part, which will supply the point of view and the missing factors which no mathematician or physicist can be expected to provide in good faith with his own profession.

Again the question is an economic one—can it be done without increase in facilities?—can it be done in a four-year program?

**M. L. Manning** (Westinghouse Electric and Manufacturing Company, Sharon, Pa.): The paper by M. G. Malti is well written and offers among other things valuable suggestions for a proposed program of engineering teacher training.

I should like to contribute to this plan of engineering teacher training from the standpoint of the practicing engineer.

For selected teachers of engineering not only graduate work equivalent to a master of science degree, or better, with minors in mathematics and physics would be desirable but also following this work with at least a three- to four-year program of practical experience in industry leading to a doctor of philosophy degree. Since engineering is about three-fourths common sense a practical basis is necessary. This experience should be in design work followed by research and development problems. In this way a not-too-theoretical frame of mind is formulated but attention is also focused on the economics of the problem. The lack of this training is often so noticeable when former teachers of engineering enter into practical work. In setting up a problem the mathematical or physical beauty so engrosses the thought that all sight is lost of the practical side or how the results are to be obtained in the laboratory.

For an example, let us consider the response of a three-mesh transformer network to an impressed impulse voltage wave. Two thoughts are uppermost in the transformer design engineer's mind; namely, the initial and final or steady-state solutions. In the intricacy of the solution, it is easy to overlook these two important practical considerations. Because of the oversight results are sometimes expressed which lead to incorrect conclusions.

If the teacher were trained to recognize such important facts by experiencing them in industry, by actually designing and following the manufacture of electrical machinery, by obtaining a knowledge of the dollars and cents part of the picture, and by noting the attitude of industry toward these problems and toward educational work as a whole, a decided improvement in the quality and relationship to industry of teaching would be noted. An attempt should, of course, be made to make the equalization balanced; that is, not to lose sight of the educational as well as the industrial processes simultaneously.

It might be argued that such a program is difficult to fulfill, but it seems to the writer a staggered plan could be formulated. Due to the uneven keel of industry at times the absorption of this teacher training by industry would vary but over a period of time a program could be devised.

For an example, let us consider the graduate program of the Westinghouse Electric and Manufacturing Company as a suggested training course. The work is co-ordinated at all plants. This means a student or engineer at the South Philadelphia works may receive graduate credit for a subject if he is transferred to the East Pittsburgh works, or to the Sharon works, etc. During the past year over 1,500 engineers and students participated in this plan and about 600 received graduate credit under the University of Pittsburgh—Westinghouse arrangement. A comprehensive program was also organized in the transformer division, the Sharon works. The average attendance for the courses was 92 per cent. The subjects included "differential equations for electrical engineers," "symmetrical components" and a well-organized transformer course. This latter course consisted of 31 sessions followed by comprehensive examinations. The classes were conducted by members of the transformer engineering department who were specialists on the particular topics studied. These topics were from one to five sessions in length. The course content follows:

1. Fundamentals (five*). The general differential equations, transformer vector diagrams, physics of the transformer, etc.
2. Practical distribution transformer design problems (two).
3. Fundamental considerations of reactance and stray losses (two).
4. Iron losses (two).
5. Magnetic forces (one).
6. Magnetic noise (one).
7. Radio interference (one).
8. Insulation (two).
9. Heating and cooling of transformers (two).
10. Condenser bushings (two).
11. Tap changers (two).
12. Inertaire equipment and oil filters (one).
13. Instrument transformers (one).
14. Distribution transformers (one).
15. Power transformers (one).
16. Constant-current regulators (one).
17. Preventive autos—series transformers (one).
18. Three-winding transformers (one).
19. Current-limiting reactors (one).
20. A-c welding transformers (one).

This course is mentioned only to suggest how other courses in electrical apparatus might be outlined for a program of engineering teacher training.

The method of presenting engineering problems as proposed in the paper by B. R. Teare, Jr., is commendable. The fact must not be overlooked that self-education at least in part is the only practicable way in which most students can acquire higher mathematics and physics. Most students fail to grasp the concept of expressing physical relations in mathematical form. The technical student often finds, upon entering a class in engineering, that he has to deal with mathematics under a new form. The particular engineering subject he is studying must be translated into mathematical terms and this causes difficulty. The sense of perspective is often lacking. This can be developed as the student becomes more mature provided he makes actual use of mathematics.

Skill in the use of mathmatics is the really essential thing. Use of arithmetic with algebra, perhaps, or a simple diagram often leads to more satisfactory results than others secured through elaborate processes involving lengthy equations and complicated operations. In the latter, errors are apt to occur, and the common-sense part of the problem is likely to be overlooked. Assumptions may be made to facilitate calculations which are physically unwarranted, as one loses sight of the physical problems in the intricacy of the mathematical solution. Abstract mathematical studies, if pursued as a kind of intellectual exercise, may produce a pure mathematician, but these studies may unfit a man for practical engineering. A tool expert is not necessarily a successful manufacturer, nor is a mathematician necessarily an engineer.

Mathematics is used in engineering to express the quantitative relations of natural phenomena. The mathematician delights in the relations. He may divorce them from the phenomena and give them abstract expression. The engineer is concerned with the natural phenomena and demands the physical conception. The medium of expressing these relations is of secondary consequence.

In summarizing, the engineer is concerned with applied mathematics. The ability to state a problem, to recognize the elements which enter into it; to see the whole problem without overlooking some important factor; to use good judgement as to the reliability or accuracy of the data or measurements which are involved and the ability to interpret the result; to recognize its physical significance; to get a common-sense perspective of its meaning and the consequences which may follow; to note the bearing of the various data on the final result, such abilities as these are of higher order than the ability to take a stated problem and work out the answer. It is this sort of judgment and insight which makes mathematics useful.

We should emphasize not the subject matter nor the students but the method of teaching. Aside from the imparting of knowledge and technical ability, the teaching of the use of mathematics and physics in engineering problems gives opportunity for training in the use of logical methods, and in the drawing of intelligent conclusions from unorganized data which will make efficient men, whether they follow pure engineering or semitechnical, or business pursuits. Such teaching does not come from the textbook, it comes from the teacher. He must be in sympathy with engineering work and have a just appreciation of its problems and its methods. He must be imbued with the spirit and the ideals of the engineer.

**M. S. Coover** (Iowa State College, Ames): Professor Curry has presented an admirable discussion on the means of co-ordinating the three major component parts of training for engineers and more particularly electrical engineers. His paper reads very much as I would hope that mine might read if I were called upon to expand the objectives as they have been written just recently for the curriculum in electrical engineering at the Iowa State College.

The problem that concerns me most is the crowding that seems to be so necessary in order to stay within a normal four-year program. The subject matter of a majority of courses is assigned to the student in such rapid sequence that even the better-than-average student finds it difficult to make a really satisfying useful assimilation either from his own viewpoint or that of his instructor. This problem may not be so serious for these institutions who have the opportunity to hand pick their students, but it is a problem the solution of which is not so easy for publicly supported institutions.

At the college which I represent there is a growing tendency on the part of the truly conscientious student to realize the value of the best training that he can get if he is to reach a satisfying place in this highly competitive social and scientific age. Accordingly, we find more engineering students taking advantage of our summer school offerings in order to lighten the number of credit hours during the winter months, thereby making available more time for the remaining courses. By this process he is spreading his training and mental efforts over the equivalent of five academic years within the space of four calendar years.

If we as teachers are intending to give to the student the best that it is possible to give him we should not only make every effort closely to co-ordinate our own work within a given department but as Curry points out, maintain a closer personal relationship among the several departments concerned.

Malti has done a good job of stating the processes involved in the handling of engineering problems from the purely technical viewpoint.

He makes the statement that something seems to be wrong either in our teaching of mathematics and physics to engineers or in the proper co-ordination of these subjects with engineering courses or both. What serious-minded student, teacher, or engineer has not entertained similar thoughts from time to time?

No doubt some of the reasons for these undesirable situations are present in various degrees in most educational institutions. Some of the remedies which Malti suggests are good. Physicists and mathematicians cannot help but improve their teaching of engineering students if they will take a closer interest in engineering and engineers. Since mathematics and physics combine to form the foundation upon which the engineering educational structure is to be built, co-operation among those concerned is essential if the structure is to be useful.

The desirability of competent teachers with an adequate education cannot be disputed. However, a man with an armful of degrees is not necessarily the best teacher. The individual is more likely to be a good teacher if he has had a reasonable amount of responsible commercial or industrial seasoning. If he has demonstrated his ability, he is more likely to know his subject better, to appreciate its significance, and therefore, more likely to be enthusiastic and inspiring, thus developing and stimulating the student's intellectual curiosity. Simply to specify a certain type of academic training for the teacher in order to qualify for an appointment is most likely to lead to what has been cited as one of the prevalent ills. If, for the sake of argument, it is granted that we do not now have good engineering teachers, how can the present teachers educate better ones along the lines suggested?

On the matter of co-operation between and among the departments of physics, mathematics, and electrical engineering, I venture with apologies to cite what we are doing at the Iowa State College for the reason that I am not familiar with what is being done along the same line at other institutions, but in so far as I am informed it is with but one exception practical only at those institutions where say the departments of physics and electrical engineering are under one and the same headship. At the Iowa State College, each of the three departments under discussion is administered separately. The instructor in the mathematics department who is assigned to the instruction of electrical-engineering students in differential equations teaches one section of junior electrical-engineering students in a-c circuits in the electrical-engineering department; exchanging with one of our own staff members who teaches one section of differential equations to engineering students in the mathematics department. It goes without saying that close co-ordination thus becomes a requisite. A similar arrangement is practiced between the departments of physics and mathematics and is being developed between the departments of physics and electrical engineering, thus closing the triangle.

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*Number of sessions.

On another point, I believe that physics and mathematics are chosen almost invariably as minors for work leading to the degree of doctor of philosophy with a major in engineering.

**Albert A. Nims** (Newark College of Engineering, Newark, N. J.): The co-ordination about which we are talking is well illustrated by the papers themselves. Professor Bryant refers to the lack of coordination in his student days among the terms and methods used to explain the quantitative relationships in electric circuits, and the performance of the different varieties of electrical machines. The present situation is reflected by Professor Curry, who refers to "training the student . . . . to search for the fundamental principles upon which a statement of the problem may be formulated . . . . since subsequent engineering courses will utilize the same principles." It might well be said that the same search should be constantly in the mind of every teacher who wishes to increase his professional effectiveness.

One of the most promising ways of increasing the efficiency of our teaching methods is so to organize our subject matter that the number of new concepts to be mastered is a minimum, and the usefulness and applicability of each is a maximum. Some indication that this search for common denominators is making progress is found in Professor Teare's references to "the analogous behavior of electric circuits, mechanical systems, and heat conduction systems, expressed in exactly similar equations," and "to the broad analogy between the space fields of electrostatics, magnetostatics, gravitation, thermal and electric conduction, and fluid flow, described by similar vector equations and identical field maps."

Not too much can be expected of this ideal simplification, however. Professor Strong has referred to the practical considerations which intrude themselves into every theoretical plan, no matter how ideal, and has mentioned the economic factor. Professors Bryant and Coover have referred to the time factor which creates a continual pressure for increased efficiency in presentation of subject matter. Another practical consideration is the mind of the student himself, which sets a practical limit to the process of searching for common denominators.

Highly generalized statements are of little use as an initial approach to the phenomena of electrical engineering. The increments of knowledge by which a new subject is mastered are limited in size. The assimilable increments vary in size with each individual, but, with our mass production methods, some working average must be used. Teaching efficiency is likely to be a maximum when the number of fundamental concepts is such that each can be acquired in the minimum number of practical steps, and each will be of the widest use after it has been mastered.

Professor Morgan has pointed out that instruction is more efficient when "laboratory and classroom courses do not exist separately; each division of the work should receive investigation in the laboratory at the same time that it is being discussed in the class room." Professor Strong has referred to the effectiveness of computation exercises for driving home fundamental relationships in the minds of the students. Computation might well be made a third approach, co-ordinate with classroom discussion and laboratory exercises. "Slide-rule pushing" and "graph plotting," when properly organized and motivated, can be potent tools with which the student can reveal to himself relationships that otherwise he might not grasp. One of the comments most frequently made about the course in winding specification and performance computation offered at the Newark College of Engineering under the name of electric machine design is to the effect that "you certainly know what goes on inside a generator after you have figured out one of those designs."

Computation is a kind of laboratory work that requires very inexpensive equipment. In fact, it is about the only kind of laboratory exercise one can have in a mathematics course. At the Newark College of Engineering at least one computation exercise per week is scheduled in the second-year calculus course. The project method, based almost entirely on computation, is the procedure adopted for studies of networks, and of transient phenomena in the junior year.

The one-semester course in transients is the outgrowth of a brief theoretical discussion given in preparation for some laboratory exercises. It naturally involves considerable work with differential equations of a few varieties. The interest aroused by this course, together with that generated by the discussion of tensor analysis in the technical press, has resulted in the scheduling of two optional after-hour courses for the juniors. One deals with differential equations for one semester, and the other with vector analysis for an equal length of time. The optional and after-hour features operate automatically to select the abler students. The courses are conducted by the head of the mathematics department, who makes no claim to being an engineer. The method of presentation involves a minimum of manipulative theory and a maximum of applications, such as engineers are constantly meeting. The results of these courses seem to be twofold: an increase of mathematical interest and understanding on the part of the students who take them, and an increase of engineering interest and understanding on the part of the teacher.

**Wm. A. Del Mar** (Habirshaw Cable and Wire Corporation, Yonkers, N. Y.): Speaking as an engineer to an assembly composed chiefly of teachers, I can pay my compliments to the teachers of mathematics and say that they have not sinned so much as been sinned against in being forced to expend their energies on refractory material.

It is quite possible that a genius of a teacher may be able to make a mathematician of almost anyone, given ample time to work with him, but in college education we are concerned with mass production and a time must assuredly be reached when the teacher realizes that certain students are by nature mathematically inept, as far as mass education is concerned. Such men should not be forced to drag their classes and develop inferiority complexes by being either flunked or allowed to proceed with nothing but a memorized knowledge of data and standard processes.

It should not be difficult to deflect into other activities men whose minds run against a blank wall in trying to express physical problems in mathematical terms.

Is it not the failure to do this that gave rise to the need of this symposium?

**W. A. Curry:** Discussion has added a number of valuable suggestions and viewpoints on this matter of co-ordination and confirms the importance and interest which this problem holds for all who are concerned with electrical-engineering curricula. It would appear that we may attempt to achieve this objective in a variety of ways, and this diversity indicates that there is no single, royal road to its realization. Only by continued vigilance can an effective co-ordination be attained and maintained through the changing years.

**M. G. Malti:** I should like very much to endorse Sorensen's ideas regarding contact with industry. I have had the good fortune of being a consultant for a manufacturing concern over a period of several years and the pleasure and stimulus which this contact with industry has given me have been reflected both in my teaching and writings. Every trip I made to the plant and every summer I spent in it have given me more insight into the practical applications of my specialty which I have conveyed to my students. It is extremely desirable, therefore, that graduate students keep in constant touch with industry either through consultation or through regular employment. Whether such men would return to teach *as instructors* after they have been in industry, for some time, is questionable.

Strong's stress on the economic problem is misplaced. The fact that a graduate student takes an assistantship to enable him to do graduate work does not necessarily imply that he makes a poor teacher. Nor is it true that a researcher is invariably absorbed by his research to the exclusion of everything else. I agree that instances do occur where a graduate student has turned out to be a poor teacher. This, however, is a fault of the individual concerned rather than of the system of using graduate students as assistants. As to computations, I am positively in favor of them and have used them in connection with my courses. But I attempt to make my computation not "slide-rule" or "formula-substitution" problems but rather problems which stimulate thought. Computing periods should, in my opinion, be periods in which the habit of straight thinking is required under competent supervision.

Nims seems to favor "slide-rule pushing" and "graph plotting" as showing the student "relationships which he otherwise might not grasp." I am sure the "graphs" themselves do reveal such relationships but I question whether the actual plotting of these graphs does! In order to illustrate what I mean let us assume that one laboratory course is run by two different instructors as follows:

*Instructor A* requires his students to run the equipment, take data, and when the experiment is over gives his instructions as follows:

(*a*) Compute only one point on each curve or perhaps only one curve, thus reducing slide-rule pushing to a minimum.

(*b*) Blue prints of all curves are given to each student. You *do not have to plot any curves* but!

(*c*) Give a complete and adequate discussion of the why, how, wherefore, of all the results that the curves reveal.

(*d*) Answer the following pertinent questions (which require thinking) regarding the results of your experiment.

This is the instructor who does not care to have his student waste time on curve plotting and slide-rule pushing. He would rather have them use their time in forming correct habits of thought.

*Instructor B* requires his students to run the equipment, take data, and when the experiment is over gives his instructions as follows:

(*a*) Compute *all points* on each curve (maximum slide-rule pushing).

(*b*) Make neat plots of *all curves* using india ink (maximum curve plotting).

(*c*) Discuss curves (by this he generally means say that this curve runs this way and that curve runs that way, which of course is obvious from the curve itself).

This is the instructor who requires "curve plotting" and "slide-rule pushing" and is the preponderant type in our engineering colleges.

Now I ask who turns out better engineers, instructor *A* or instructor *B*?

Del Mar puts his finger on the right spot when he states that our present plight is due to mass education in engineering. Now it so happens that other professions have solved this problem of mass education by limiting enrollment. This is true of the medical, dental, and legal professions. Engineering as a profession has, so far, not seen fit to take this step which, in my opinion, is the only solution to the problem.

Coover raises the question of how the present teachers can educate better ones if they are not so good themselves. My answer is that Coover begs the question. I neither did condemn nor even had the intention of condemning *all* engineering teachers. Thank God there are high-grade teachers scattered throughout this land. It is these who would and could educate better ones along the lines suggested.

Manning and I are in full agreement. The value of co-operation between industry and the universities is unquestionable. They both have something to offer to each other and a mutual exchange is extremely desirable. I should like to see a plan instituted whereby a large number of engineering teachers throughout the country are afforded a chance to spend their summers in industrial concerns. I also commend Manning's statements that mathematics and physics are valuable to the engineer not perhaps so much because of their subject matter but because of the training they afford him in logical reasoning and in correct processes of thought.

# Self-Excitation of Induction Motors

By C. F. WAGNER
MEMBER AIEE

**Synopsis:** It has been known for some time that an induction machine whose rotor is driven mechanically may become self-excited if capacitors are connected across its terminals. The present paper is concerned with the predetermination of the machine characteristics when operating under such conditions. The frequency of excitation is very close to the synchronous frequency corresponding to the speed of the rotor. The voltage to which the machine will excite is dependent upon its no-load excitation characteristics at that frequency, the criterion to be satisfied being that the lagging volt-amperes of excitation equal the leading volt-amperes of the capacitors.

Under load, similar criteria must be satisfied. Voltage conditions are determined by a cut-and-try solution such that the summation of reactive volt-amperes equals zero. The slip is then obtained from the relation that the summation of the real power equals zero. These relations have been applied to various types of loads, such as pure resistance and inductive resistance, single-phase and three-phase and also to induction-motor load. Excellent checks between test and calculated results have been obtained.

THE general impression appears to exist that for an induction machine to operate either as a motor or as a generator a source of alternating potential is always necessary in order to supply the excitation requirements. Such is not the case, for under certain conditions, an induction machine may supply power as a generator without a source of alternating potential, the magnetizing current being supplied by static capacitors. It is the purpose of this paper to discuss the circumstances under which such operation becomes possible.

The fact that such operation is possible has been known for some time, but very little has been written upon the subject until recently. The reason for this paucity of papers and articles lies in the relatively minor practical importance of the subject. However, the increased use during the past few years, of capacitors for power-factor correction, has placed a new aspect upon this problem. If the power supply to an induction motor is disconnected, the inertia of the connected rotating load tends to continue the rotation of the armature. The extent to which this occurs is dependent upon the nature of the load and in certain cases the armature may continue to rotate for seconds or minutes. In addition, applications are known in which gas or gasoline motors are connected to the same shaft with the induction motor and the utilization device, so that, in the event of the removal of the electric-power source, the armature can actually increase in speed and remain at the increased speed until manual readjustments are made. With capacitors connected across the terminals of induction machines which have been disconnected from the electrical source and in which the armature continues to rotate, the value to which the terminal voltage will rise due to self-excitation is dependent upon the speed, value of the capacitor, and load. With the regulatory function of the power source removed the terminal voltage may rise to dangerously high voltages—dangerous with regard to human life or dangerous with regard to insulation breakdown. Parallel-connected lights might also burn out with but a nominal increase in voltage. It may be seen, therefore,

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1. For all numbered references, see list at end of paper.

that this problem has been removed from one of purely academic interest to one of practical importance.

In 1935, Bassett and Potter[1] presented test results showing the performance of generators under capacitive and combinations of resistance and capacitive loading. The present article considers similar problems and further shows that the performance under such conditions, including both balanced and unbalanced operation, can be precalculated quite accurately.

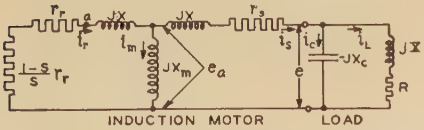


**Figure 1. Equivalent circuit of induction generator with three-phase load of capacitors $-jx_c$ in parallel with induction load $R + jX$**

With known conditions the characteristics of the machine can be predicted by the methods presented here.

## General Considerations

The conventional equivalent diagram of the induction motor will be used with the exception that the magnetizing branch will not be regarded as constant but must vary in the manner dictated by the saturation characteristics of the particular machine. This circuit is shown in figure 1 for one phase. The symbols will have the following significance:

$r_s$ = Stator resistance in ohms per phase to neutral
$r_r$ = Rotor resistance in ohms per phase to neutral
$x$ = Stator and rotor leakage reactances in ohms per phase to neutral
$x_m$ = Reactance of branch representing magnetizing current in ohms per phase to neutral
$s$ = Slip expressed as a fraction of synchronous speed

The slip is referred to the frequency of the stator voltages and currents and, when operating as an induction generator, is, of course, negative.

The general considerations which will be applied in determining the solutions are that the summation of the real power and the summation of the reactive volt-amperes throughout the entire circuit, including that of the load, must each equal zero. Because of the presence of saturation phenomenon, resort will be had to a graphical or a cut-and-try method of solution.

Most of the tests which are described in what follows were made on a 15-horsepower, three-phase 60-cycle 220-volt 1,770-rpm type *CS* Westinghouse motor of conventional design. The constants, obtained from test data, are

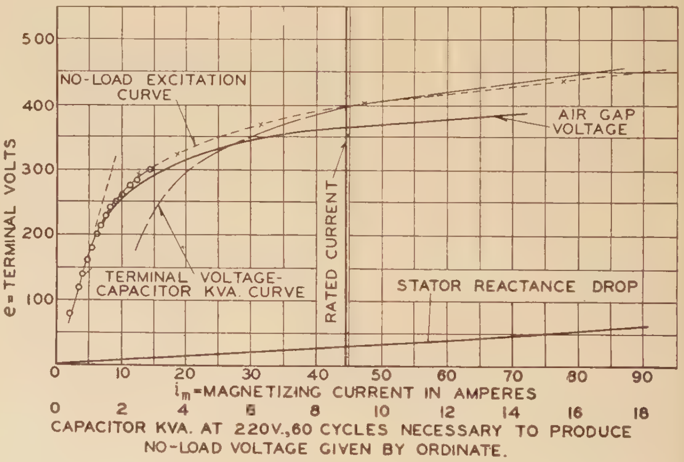
$r_s$ = 0.151 ohm per phase to neutral
$r_r$ = 0.145 ohm per phase to neutral
$x$ = 0.394 ohm per phase to neutral
$x_m$ (air-gap line) = 19.8 ohms per phase to neutral

The no-load saturation curve is given in figure 2. The lower portion of this curve, indicated by circles, was obtained by impressing a three-phase alternating voltage to the machine terminals and varying the speed by means of a connected d-c motor so that the power input from the a-c end was zero.

**Figure 2. No-load saturation curve of 15-horsepower 220-volt 60-cycle induction motor**

o = motor connected to a-c source

x = motor excited through capacitors



## No-Load Excitation

A three-phase bank of static condensers was connected (without the a-c supply) across the terminals of the machine and the rotor driven at a speed corresponding to normal synchronous speed by means of the d-c motor. Since only the losses of the machine must be supplied, the quantity, $\frac{1-s}{s} r_r i_r^2$ (figure 1) which represents the shaft input, will be very small. This condition requires that $s$ be very small and consequently that $\frac{1-s}{s} r_r$ be large and $i_r$ small. The equivalent network for this operating condition for all practical purposes reduces to that shown in figure 3 in which $r_s$ of figure 1 has also been neglected. Because $s$ is small the generated frequency corresponds to that of the shaft which in this case is normal frequency. Upon varying the magnitude of the capacitors the test points, indicated by crosses in figure 2, were obtained, extending the no-load excitation curve to more than ten times normal excitation current. It will be observed that over the portion of the range for which the data overlap, the test data checks with that obtained by the application of an alternating voltage. Referring to the equivalent circuit of figure 3 it may be seen that the ratio $\frac{e}{i_m}$ for any point on the no-load excitation curve must equal $(x_m + x)$ or $x_c$. In order that the reactive kilovolt-amperes sum up to zero, $x_c$ must equal $(x_m + x)$. Thus the slope of a straight line drawn from the origin of the curve of figure 2 to any point on the curve gives the capacitive reactance of the capacitor required to produce that voltage at no load. As the condenser capacity decreases the slope representing its capacitive reactance increases and the terminal voltage decreases. When finally the slope equals the air-gap line, an infinite number of solutions are possible. Beyond this point the machine is inoperative. Therefore, there exists a certain minimum amount of capacitors which will still produce self-excitation. In this regard the induction generator performs in a manner quite analogous to a shunt-excited d-c generator.

In what follows it will be necessary to know the volt-ampere characteristics of the $x_m$ branch alone. This is obtained from the dotted line in figure 2 by subtracting the $xi$ drop giving the curve shown by the full line and marked "air-gap voltage."

A further demonstration of the truth of the above theory is offered by the manner in which the terminal voltage changes with change in frequency. The full lines in the insert of figure 4 show the magnetizing characteristic and the capacitor characteristics for normal frequency. As the frequency is increased the terminal voltage for a given magnetizing current increases proportionately with the frequency. On the other hand, the capacitor current varies inversely proportional to the frequency. These characteristics are shown by the dotted lines for an increase in frequency of about 20 per cent. The new terminal voltage is then given by the intersection of the dotted lines. The comparison between test and calculated results using this method is shown by the circles and crosses in figure 4, which indicate a very close agreement.

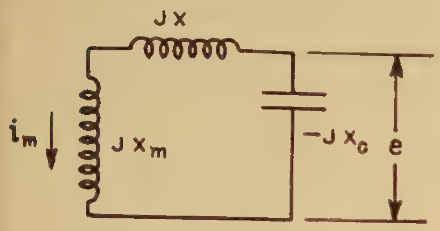


**Figure 3. Equivalent single-line diagram for no-load excitation condition**

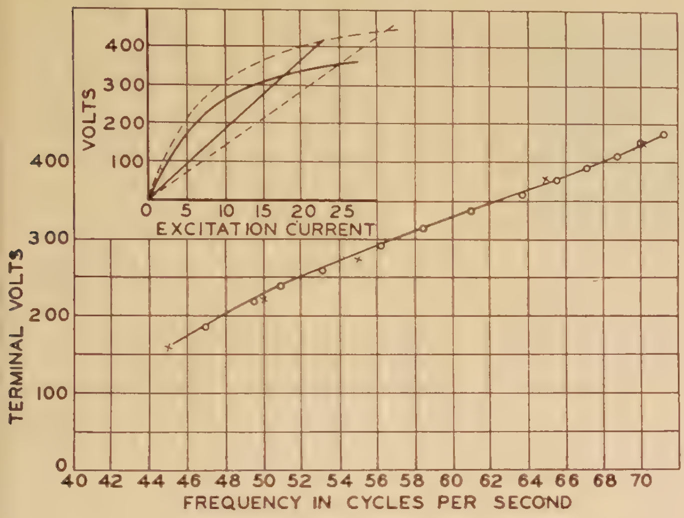


**Figure 4. Effect of change in frequency**

No load—constant shunt capacitor = 10.6 kva at 60 cycles

o = test points

x = calculated points

In order to provide a better quantitative perspective of the values involved, the dashed line in figure 2 was calculated. This curve gives the terminal voltage as a function of the kilovolt-amperes of the capacitors at normal frequency and voltage. It will be seen that for a capacitor whose kilovolt-amperes is equal numerically to the horsepower rating of the machine the terminal voltage reaches a value equal to twice normal. This will vary within limits for different motors, depending upon their excitation characteristics.

## Three-Phase Impedance Loading

To determine the regulation characteristics under polyphase conditions, the induction generator was loaded with three resistance racks, which upon measurement were found to have 8.3-per cent reactance at 60 cycles. With a constant capacitor bank the load was changed keeping the load frequency constant with the result shown in figure 5. The circuit under consideration is shown complete in figure 1. To calculate the performance while keeping the capacitor fixed the following steps are involved. An arbitrary value of $R$ and its corresponding value of $X$ are chosen for which it is desired to determine the terminal voltage, $e$. Estimate the value of $e$. This fixes $i_L$ and $i_c$. The current $i_s$ is the sum of $i_c$ and $i_L$. Knowing $i_s$ the drop through $r_s + jx$ is found which determines $e_a$. The magnetizing current $i_m$ is obtained from the full line of figure 2. And, finally, $i_r$ is the sum of $i_m$ and $i_s$. At this point all the currents are determined for the estimated values of $e$. All of those operations are, of course, vector operations. If the estimated value of $e$ is the solution the following relation should be satisfied.

$$Xi_L^2 + xi_s^2 + e_a i_m + xi_r^2 - x_c i_c^2 = 0 \quad (1)$$

If, however, this summation is not satisfied a different value of $e$ should be tried.

The comparisons between the test and calculated results for two values of capacitors are shown in figure 5.

The slip for this particular value of $R$ is determined by summing up the power quantities for the solution obtained from the summation of reactive volt-amperes and equating this sum to zero. No cut-and-try method is necessary. Thus

$$\frac{1-s}{s} r_r i_r^2 + r_r i_r^2 + r_s i_s^2 + i_L^2 R = 0$$

or, combining the first two terms and solving

$$s = -\frac{r_r i_r^2}{r_s i_s^2 + i_L^2 R} \quad (2)$$

Values of $s$ obtained by this method are shown in figure 5.

Calculated curves for pure resistance load and for the same capacitors are plotted in figure 6. It will be observed that the regulation is very much better. The series reactance in the load for the former case, although only 8.3 per cent, exerted considerable influence upon the terminal voltage.

An interesting condition exists for the range of operation indicated by the dotted lines in figure 6. Note that for this range there is no appreciable saturation so that $x_m$ can be represented by a constant. It is possible, therefore, to determine the impedance of all that portion of the cir-

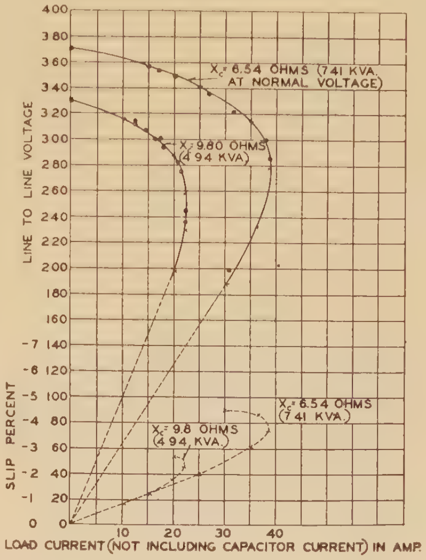


**Figure 5. Characteristics of a 15-horsepower induction generator under three-phase resistance load having 8.3 per cent reactance**

x = calculated points

o = experimental results

——— = terminal voltage

– – – – = slip

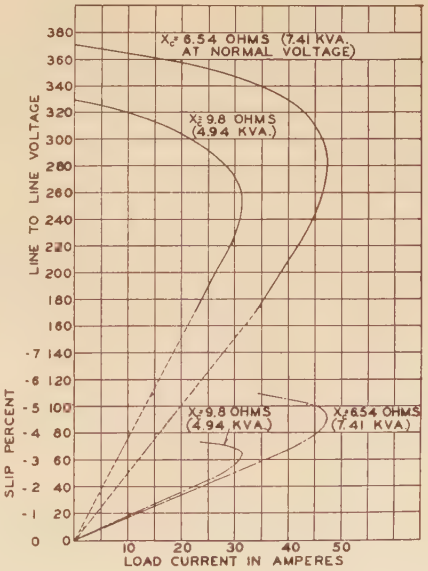


**Figure 6. Calculated characteristics of a 15-horsepower induction generator under three-phase resistance load**

——— = terminal voltage

– – – = slip

cuit in figure 1 which lies to the right of $a$. A solution exists when this impedance is purely real, there being no imaginary part. Since for pure resistance load of figure 6, $X$ is zero, then $R$ and $-jx_c$ in parallel become $\frac{-jx_cR}{R-jx_c}$ which will be designated by $R'+jX'$, in which

$$R' = \frac{x_c^2R}{R^2+x_c^2} \tag{3}$$

and

$$X' = \frac{x_cR^2}{R^2+x_c^2} \tag{4}$$

The impedance to the right of $a$ then becomes

$$\frac{jx_m((R'+r_s)+j(x+X'))}{(R'+r_s)+j(x+X'+x_m)}+jx$$

The condition that the imaginary component of this expression equals zero, results in the following equation:

$$\begin{aligned}(x+X'+x_m)[x_m(x+X')+{}\\ x(x+X'+x_m)]+{}\\ (R'+r_s)(x_m+x)=0\end{aligned} \tag{5}$$

Upon substituting (3) and (4) into (5), a fourth degree equation in $R$ results, which permits the determination of $R$. The quantity $R$ is equal to $\frac{1}{\sqrt{3}}$ times the slope of the dotted lines in figure 6. The significance of this expression is that there are an infinitely large number of solutions for the terminal voltage when $R$ has the value satisfied by this equation. Actual operation is impossible at any of these values as an attempt to operate on the straight part of the curve results in instability. For values of $R$ slightly smaller than this critical value the machine loses voltage, is unstable. A self-excited induction machine cannot, therefore, supply a sustained short-circuit current. A similar expression can also be derived for the dotted lines in figure 5, the slope of which represents the limiting ratio of $\frac{\sqrt{3}\,e}{\sqrt{R^2+X^2}}$ which still permits operation as a generator.

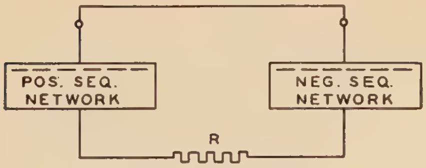


Figure 7. Method of connecting sequence networks

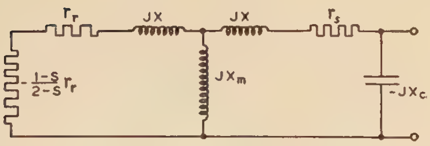


Figure 8. Negative-sequence network of induction motor with three-phase capacitor across its terminals

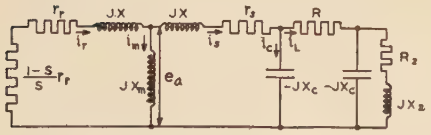


Figure 9. Equivalent circuit for induction generator and three-phase capacitor loaded single-phase by resistance R

## Single-Phase Impedance Loading

For this case let it be assumed that a resistance $R$ is placed across phases $b$ and $c$ of the induction generator, the capacitors still being connected across all three phases. This is analogous to the short-circuit of a three-phase system through a resistance $R$, a case treated frequently in the literature.[2] For this case the positive- and negative-sequence networks are connected together as shown in figure 7. The actual current through the resistor $R$ is $\sqrt{3}$ times the positive- or negative-sequence current flowing through $R$ in the diagram. This procedure tacitly assumes the justifiability of superposition in the presence of saturation phenomenon. It will be assumed that saturation effects influence only the positive-sequence network and not the negative-sequence network. The checks obtained by comparison between the calculated and test values justify these assumptions. The positive-sequence network of the machine is the same as has been considered previously in this paper and the negative-sequence network, with the exception of the capacitors, has been treated previously in the literature.[3] This network is reproduced in figure 8. Since $s$ is usually small, a good approximation is to assume $s$ equal to zero and to combine $r_r$ and $-\frac{1-s}{2-s}r_r$ making the sum equal $\frac{r_r}{s}$. It will be assumed that $x_m$ can be replaced by a constant term determined by the air-gap line. It is thus possible to replace the negative-sequence network of figure 8 by a simple impedance independent of saturation and slip. The resultant combined network for the positive- and negative-sequence is therefore that shown in figure 9; $R_2+jX_2$ is the impedance to which the network of figure 8 has been reduced neglecting the impedance of the capacitors $-jx_c$. The current in the load is equal to $\sqrt{3}$ times the current in $R$ and armature or load voltage is $\sqrt{3}$ times the voltage across $R$.

If the load is an impedance instead of a pure resistance, it is only necessary to replace $R$ by $R+jX$ where $X$ represents the reactance of the load. Tests and calculations upon the foregoing basis have been made on the previously used induction motor excited with capacitors across three terminals and loaded with a resistance rack across two terminals. The rack possessed 8.3 per cent reactance.

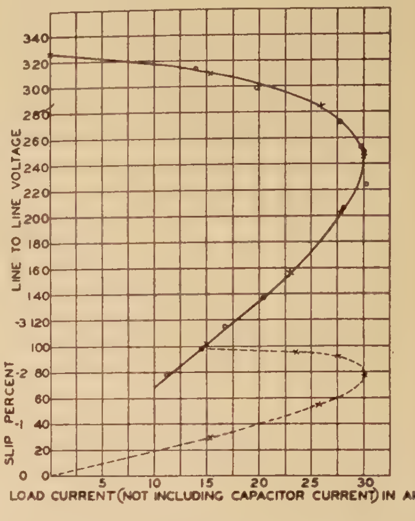


Figure 10. Characteristics of a 15-horsepower induction generator under single-phase resistance load having 8.3 per cent reactance and a three-phase capacitor equal to 10.3 ohms per phase to neutral (4.7 kva)

x = calculated
o = experimental
——— = terminal voltage
– – – – = slip

The results of these tests and calculations are plotted in figure 10, which shows very close agreement.

If a capacitor is connected across the load only then the two capacitors $-jx_c$ of figure 9 must be removed and a single capacitor having the impedance of the actual capacitor must be connected across the load impedance.

## Load Characteristics

Under certain conditions an induction generator driven by an engine or other equivalent motive power might have connected to it other induction machines which had also been connected to the source of supply. At the time of failure of the a-c source of supply the engine-connected induction motor tends to drive the other induction machines at a frequency determined by the speed characteristics of the motive power and at a

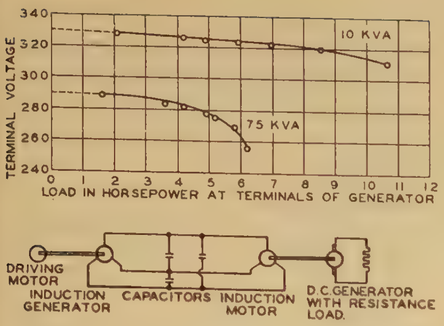


**Figure 11. Self-excitation characteristics of two 15-horsepower induction motors, one of which is driven as an induction generator feeding the other as an induction motor. Figures on curves represent capacitor kilovolt-amperes at 220 volts, 60 cycles**

voltage determined by the shunt-connected condensers. In figure 11 is shown a test setup to determine the characteristics of an induction motor when operating under such conditions. The setup consists of two of the above-mentioned motor-generator sets, the induction machines having the characteristics of those described previously. One of the d-c machines acted as a motor to drive one of the induction machines as an induction generator and the other induction machine drove the second d-c machine which was loaded upon a resistance rack. The two induction motors were connected in parallel and a bank of condensers connected across their terminals. Under this type of operation, theory dictates that the capacitors supply not only the excitation requirements of both induction motors but also the leakage reactance volt-amperes of the two machines. The curves of this figure show the characteristics at 60 cycles for constant values of capacitors as the load is increased on the induction generator. The no-load values of the voltage correspond to the values obtained previously for the no-load condition. It will be observed that the upper of these curves is much flatter than the lower one. The reason for this is apparent when it is considered that as the load is increased, the increase in leakage reactance volt-amperes of the machine must be supplied from the decrease in volt-amperes required by the excitation. At the higher voltages produced by the larger condenser capacity the machine is operating at a higher saturation and, therefore, more reactive volt-amperes is released for a given change in excitation voltage.

For the particular values of condenser capacity used in these tests, it was necessary to bring the driven induction motor up to speed by its d-c machine in order to make the sets excite themselves and carry load. However, at the no-load condition discussed previously, the machine came up to voltage very rapidly provided there was sufficient capacitor kilovolt-amperes to provide the excitation. In the loaded case, the capacitor kilovolt-amperes was too low to supply both the excitation requirements and the leakage reactance volt-amperes of the machine. Subsequent tests in which a five-horsepower 550-volt induction motor was used for the load both sets were excited very nicely by either bringing the two machines up to speed simultaneously by the one driving motor or by first exciting the induction generator and then connecting the five-horsepower machine. The question merely resolves itself into one of whether a given capacitor can supply both the excitation kilovolt-amperes of the generator and the starting lagging kilovolt-amperes required by the stationary motor.

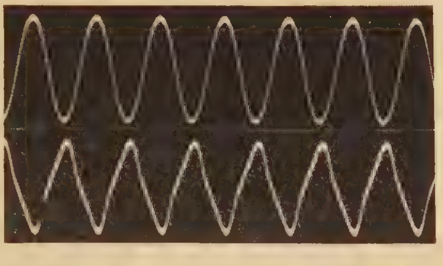


**Figure 12. Wave forms for a 15-horsepower, 220-volt three-phase induction motor operating at no load and excited by a five-kilovolt-ampere static capacitor**

Upper curve—terminal-to-terminal voltage = 320.4 volts

Lower curve—armature current = 18.3 amperes

## Wave Shape

Oscillograms of terminal voltage under either no load (figure 12) or load (figure 13) indicate a very close approximation to sine wave. The current wave forms are distorted to some extent.

## Conclusion

Calculations have been made for several conditions, both at no load and under load and the results agree closely with the test results. These checks include both balanced and unbalanced operating conditions. It is felt from this that, given the motor characteristics, the self-excitation effects can be predicted in advance to the same degree of accuracy as that of the information.

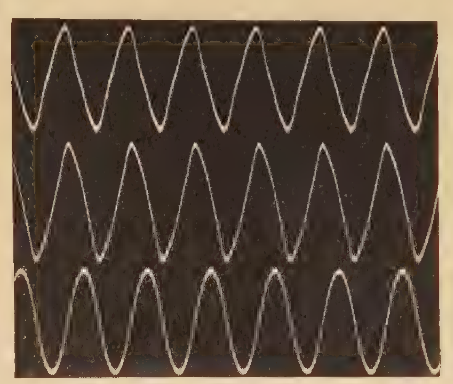


**Figure 13. Wave forms for a 15-horsepower 220-volt three-phase loaded induction motor excited by static capacitors**

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1. Capacitive Excitation for Induction Generators, E. D. Bassett and F. M. Potter. Electrical Engineering (AIEE Transactions), May, 1935, page 540.

2. Symmetrical Components (a book), C. F. Wagner and R. D. Evans. Page 43.

3. Symmetrical Components (a book), C. F. Wagner and R. D. Evans. Page 349.

# Use of Bismuth-Bridge Magnetic Fluxmeter for A-C Fields

By G. S. SMITH
MEMBER AIEE

THE methods most often used for the measurement of d-c, a-c, and transient magnetic fields depend upon one fundamental law: that a voltage is generated in a conductor cutting lines of magnetic flux. However, for each of these fields the apparatus and procedure are entirely different. Perhaps the greatest difficulty arises in the study of a magnetic field under transient conditions, since the resulting voltage oscillogram is a composite of several components having more or less intricate phase relations. Thus the actual magnetic-field values or changes are rather difficult to obtain. A single instrument, adapted for use in any of the three fields, would be very desirable. With this object in view, the following report describes the work done in attempting to use, for the measurement of a-c and transient magnetic fields, an instrument previously proposed for use only in the d-c field.

## Analysis of Problem

In a previous paper[1] an instrument for measuring d-c magnetic fields was described which gives a continuous and steady reading when placed in the field to be measured. Its operation depends upon the change in electrical resistance bismuth exhibits when placed in a magnetic field. Two bismuth resistors are placed in the opposite arms of a wheatstone bridge and in zero magnetic field the bridge is accurately balanced by using some ordinary resistance material in the remaining arms. When placed in a magnetic field the bridge is unbalanced by an amount depending upon the effect of that field upon the bismuth resistance. Thus the current or voltage due to this unbalance can be calibrated directly in terms of the magnetic field density. To avoid changes in the zero setting of the meter, due to temperature variation, all resistors in the bridge are adjusted to have the same temperature resistance change.

During the investigation covered by the previous paper the meter was tried in an a-c magnetic field and a definite reading was obtained, but no quantitative tests were attempted at that time. By substituting an oscillograph vibrator in the fluxmeter position in figure 1, the oscillogram shown in figure 2 was obtained, indicating that the meter could also be adapted to transient-flux measurements. This report describes the work done in altering the design of the same instrument so that it can be calibrated for use in a-c magnetic fields, or used for transient-flux investigations.

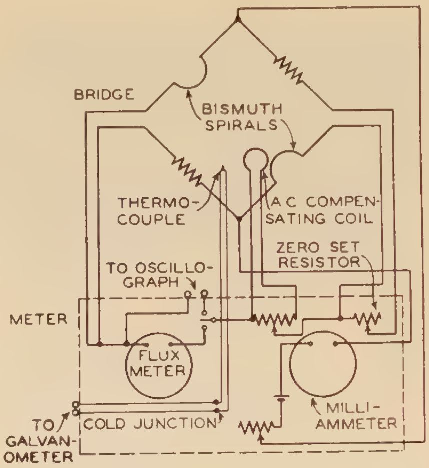

Figure 1. Wiring diagram for magnetic fluxmeter and bridge

The fluxmeter current shown by *A* in figure 2 is a composite of two current components a portion of which has been sketched in on the oscillogram. Although they have not been drawn to exact scale, it can be seen that the pulsating component which remains positive at all times represents the effect of the magnetic flux upon the bismuth resistors, and is more clearly shown in later oscillograms, while the other alternating component is merely due to an induced voltage in the coils of the bridge. This indicates that the bridge is not entirely noninductive.

The first problem was to design the bridge element so that it would be as nearly as possible noninductive. Some means must then be provided to balance out of the fluxmeter branch circuit any a-c voltage still induced. Finally the use of the bridge in a-c and transient magnetic fields must be studied to determine whether or not it does give consistent results in a-c fields, and, as far as the apparatus available will allow, determine its limits with respect to frequency.

## Changes in Construction of the Instrument

To reduce the self-inductance of the bridge element, the wire for the various resistors was enameled and was wound in noninductive spirals, with the turns as closely together as possible. This winding also resulted in a smaller coil, for the same resistance, than was obtained in the instrument previously described. To eliminate any possible voltage generation between the bridge terminal and the resistor coils, all leads were made of copper foil of similar shape and size, and were stacked one upon the other, each insulated from the next by a thin film of paper. The details of this construction are clearly shown in figure 3.

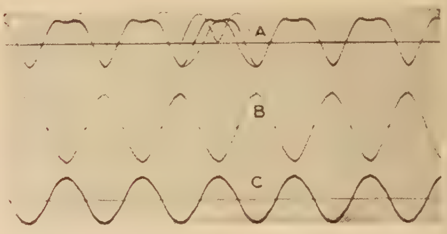

Figure 2. Oscillogram showing the distorted fluxmeter current before the bridge is provided with an a-c compensating coil

*A*—Current in fluxmeter
*B*—Induced voltage from exploring coil in air gap of magnet
*C*—Voltage across the exciting coils of magnet

A number of other improvements were made in the bridge element. Either lead or tin wire was found very satisfactory for use as balancing resistors, since they are nonmagnetic and have temperature coefficient of resistance about equal to or slightly higher than the coefficient for bismuth. By use of either, a slight negative reading previously experienced under certain conditions was entirely eliminated, as will be more fully discussed later. To stiffen the end of the bridge and more adequately to protect the resistor coils, the leads were tapered to a point near the coil end, in order that pieces cut from thin celluloid and shaped to extend around the outer edges of the coils might be

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[1] For all numbered references, see list at end of paper.

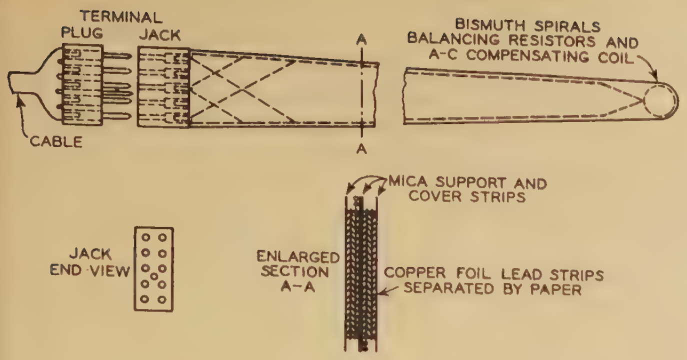
TERMINAL
PLUG
JACK
CABLE
A
A
BISMUTH SPIRALS BALANCING RESISTORS AND A-C COMPENSATING COIL
MICA SUPPORT AND COVER STRIPS
JACK END VIEW
ENLARGED SECTION A–A
COPPER FOIL LEAD STRIPS SEPARATED BY PAPER

**Figure 3. Bridge and terminal block assembly**

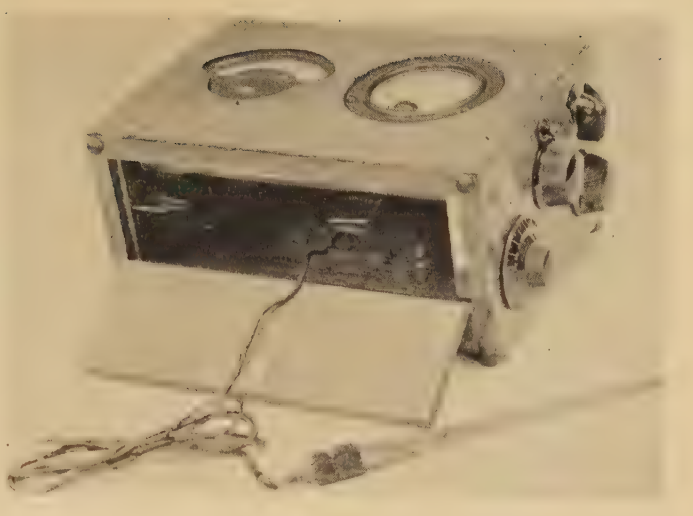

**Figure 4. View of completed meter**

cemented very securely to the mica support. The terminal block was divided into two parts, with the flexible leads to the instrument securely soldered into plugs in the one part, and corresponding jacks soldered to the copper-foil leads in the other. This method allows the bridge to be easily detached for checking or repairs, but is of most value in making adjustments during construction. By this means also two or more bridges may be used with the same meter. For example, the element of one bridge may be very small in diameter for measuring fields of very small area, while another may be designed with a much larger area, but sensitive to much lower field densities.

To balance out any a-c voltage still generated in the bridge coils, an a-c compensating coil of two or three turns of copper wire was wound around the outside of one set of the bridge coils. The terminals of this coil were carried to the meter and connected across a resistance, an adjustable portion of which is in series with the fluxmeter, as is shown in figure 1. By means of an oscillograph this adjustment may be set to give zero a-c current in the fluxmeter branch when the bridge is in a strong a-c magnetic field and the meter battery circuit is open. No difficulty was experienced in making this setting, and once it was made no further alteration was needed. When the instrument is used for direct current this coil has no function and is virtually outside the working circuit.

The controlling and indicating portion of the instrument was not greatly changed. For use with the oscillograph, two extra terminals were added, and a single-pole double-throw switch was provided to throw either the milliammeter or the oscillograph terminals into the flux-measuring position. The completed instrument, ready for use, is shown in figure 4.

The experimental tests may be divided into three groups: calibrations, phase relations, and examples of transient oscillograms.

## Calibration Tests

For use in most of the tests, an electromagnet with a core of laminated transformer steel was designed and constructed. The pole faces of the square core were tapered and turned to a diameter of about four centimeters, and were spaced with an air gap of about 0.5 centimeters. With this magnet an a-c flux density of from eight to ten kilogausses could be obtained, though at the higher values the core would become noticeably warm.

The average value of the a-c magnetic-flux density was calculated from the area, the number of turns, and voltage induced in an exploring coil placed in the air gap. Three different exploring coils were used, each with a diameter of about 3.2 centimeters, and with 2, 30, and 100 turns, respectively, of number 38 enameled copper wire. The induced voltage was measured by means of a 15-volt rectifying type of voltmeter, with a resistance of 2,000 ohms per volt. The frequency was held at the proper value by using an oscilloscope to compare it with the power company's 60-cycle current upon which the electric clocks depend.

A check on the results obtained by the rectifying voltmeter was made by means of a high-grade thermocouple voltmeter. In this case the induced voltage was obtained by adding the computed drop in the coil to the voltmeter reading. The two methods checked very closely. For the major portion of the calibration work a good sine-wave voltage source was used as far as possible. Later distorted wave shapes were also used to check the calibration on non-sine waves.

The calibration curves for a constant temperature of 22 degrees centigrade, and for three different values of current supplied to the bridge circuit are shown in figure 5. All calibration curves made by means of direct current are shown in full lines; those for alternating current are shown in dashed lines. In all the a-c calibrations the average value of flux was used. Since the rectifying type of voltmeter indications are proportional to the average values, its reading will

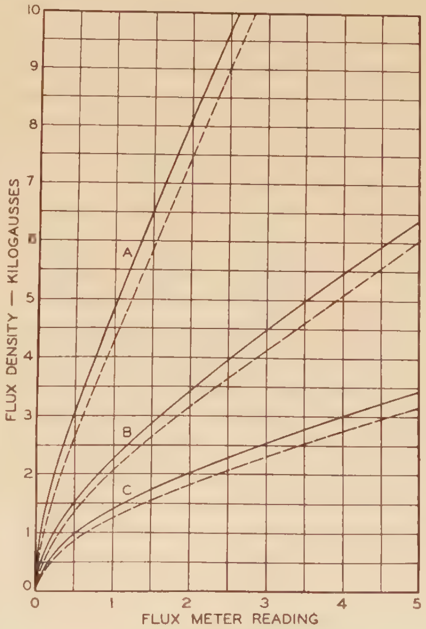

**Figure 5. Calibration curves for magnetic fluxmeter**

All curves taken at 22 degrees centigrade
Full lines indicate d-c calibrations
Dashed lines indicate a-c calibrations
Average values of a-c flux used throughout
*A*—Calibrations using three milliamperes in bridge
*B*—Calibrations using ten milliamperes in bridge
*C*—Calibrations using 25 milliamperes in bridge

indicate average values regardless of the voltage wave shape. In making checks with the thermocouple type of meter, care was used to select a good sine wave of voltage as the source.

The change in the resistance of bismuth when placed in a magnetic field varies somewhat with the temperature at which the bismuth is maintained. The change becomes less per unit of flux density as the temperature is increased. In the previous paper where only d-c fields were used this change was indicated by calibration curves at several different temperatures. The same changes take place when used for alternating current though the actual calibration curves at other temperatures are not shown. While this change is not quite linear with respect to temperature, over the usual range, the actual flux densities are roughly one per cent per degree lower for lower temperatures, or higher for higher temperatures, than the values shown for 22 degrees centigrade. Where more accuracy is desired, the values must be interpolated from a set of calibration curves covering the temperature involved, or by means of an empirical formula derived from such curves or data.

The a-c calibrations were carried out for frequencies varying from 12 to 540 cycles per second. Below 12 cycles the instrument pointers vibrated too much for reading. No apparatus was available to go above 540 cycles; in fact only the lower portions of the curves could be checked for this frequency. Where possible, portions of all curves were checked by means of two or more of the three exploring coils. All values taken over this range of frequencies, and in checking by means of the different exploring coils, were seldom over two per cent above or below the average value shown. Since the guaranteed accuracy of the rectifying voltmeter is only four per cent, these values appear quite satisfactory. No tendency whatever appeared for the values taken at the higher frequencies to be either higher or lower than the others.

Seemingly the direct current and the average values for the alternating current should fall on the same curve, but the experimental data proved this to be not so. Were this caused by the lag of the resistance change as found by Konig[2,3] more flux would probably be necessary to give the same meter reading rather than less, and the effect should increase as the frequency increased. Nor could it be accounted for by eddy-current losses, inductance, or capacity in the circuit since these would vary with frequency and would also tend to reduce rather than increase the sensitivity of the meter. The most logical explanation is suggested by the wave shape of the fluxmeter current oscillograms shown most clearly in figures 7 and 9. Because of the nonlinear relation of the flux density to the resistance change, as is evident by the direct-current calibration curves, the resulting variable current in the bridge circuit is decidedly non-sine wave when produced by a sine wave of flux. Since the torque in the direct-current meter used as a fluxmeter depends upon the average of this cyclic current, this average, due to the flat-topped waves, would be somewhat higher than for sine waves of similar amplitude and thus the reading for the average value of the alternating-current flux would be greater than would be obtained were the meter current waves sinusoidal.

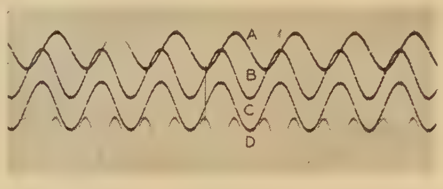

**Figure 6.** Phase relations at 60 cycles per second

A—Current in the coil of magnet
B—Voltage across coil of magnet
C—Induced voltage from exploring coil in air gap
D—Magnetic flux in air gap by means of fluxmeter

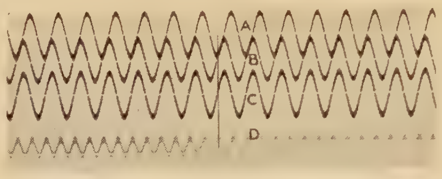

**Figure 7.** Phase relations at 280 cycles per second

A—Current in coil of magnet
B—Voltage across coil of magnet
C—Induced voltage from exploring coil in air gap
D—Magnetic flux in air gap by means of fluxmeter

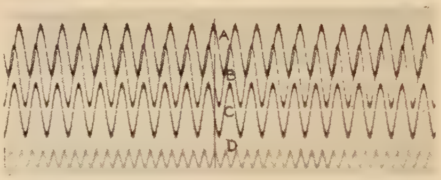

**Figure 8.** Phase relations at 480 cycles per second

A—Current in coil of magnet
B—Voltage across coil of magnet
C—Induced voltage from exploring coil in air gap
D—Magnetic flux in air gap by means of fluxmeter

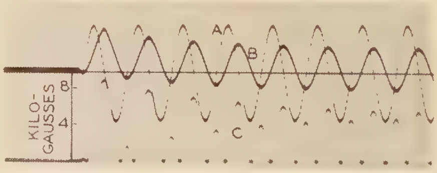

**Figure 9.** Starting transient when a-c voltage is switched across coil of magnet

A—Induced voltage from exploring coil in air gap
B—Current in coil of magnet
C—Magnetic flux in air gap by means of fluxmeter

No difference could be detected in the readings when the wave shape was distorted as compared to sine waves. Also since the highest frequency used is a rather high order of harmonics for the lowest and the calibration for all frequencies used fell on the same calibration curve, it seems evident that within the range of frequencies covered the accuracy of the meter is not noticeably affected by the wave shape of the flux.

The accuracy with which readings could be duplicated or checked between different meters, using reasonable care in determining the temperature, was seldom over two per cent in error when used for direct current. Only the one meter for use in alternating current has so far been constructed and calibrated; thus it would be difficult to state what accuracy could be expected, since the apparatus used for calibration could not be depended upon for an accuracy of more than four per cent, and this was the only possible means of obtaining a comparison.

## Phase Relations

The second problem was to study the time-phase relations of the bismuth resistance and magnetic flux as they were varying. Investigations made in this field by Konig, Heurlinger, and others,[2–5] indicate a lag of the bismuth resistance change. Konig, who probably made the most extensive investigation, used a make-and-break device to produce changes in the magnetic field. This would probably be equivalent to using a rather high alternating frequency. The problem attempted in the present research was limited to what might be termed commercial frequencies and their harmonics.

For such study a series of some twenty or more oscillograms were taken over a range of from 60 to 480 cycles per second. Representative oscillograms for 60, 280, and 480 cycles per second are shown in figures 6, 7, and 8.

No lag in the resistance change can be detected at 60 cycles, but at 280 cycles a lag appears of about 14 electrical degrees, and at 480 cycles this has further increased to about 24 electrical degrees. However, these measured lags must not be considered more than approximate, since the oscillograph light and vibrator adjustments can often cause slight apparent phase shifts when none are present. For example, in figure 6, the magnetic-flux record appears slightly to lead the voltage values. The conclusions stated are based upon the average results of the large number of oscillograms taken. Unusual care was exercised in taking sets with the minimum of changes in adjustments, while other sets were purposely taken after adjustments had been changed.

## Magnetic Transients

The third problem was to obtain some transient oscillograms of the magnetic field, together with the corresponding current and voltage values. The oscillogram in figure 9 shows the switching of a 60-cycle voltage across the coil of the magnet previously described. The unusual height of the transient-flux values gives an indication of the instantaneous mechanical forces acting during the transient period. The usual transient and steady conditions when a single-phase alternator is short circuited are shown in figure 10. The variations in the field current *C* after short circuit give some indication of the armature reaction on the field flux but the actual flux variations in *D* show exactly how the air-gap flux is varying as well as its phase relations to the field and armature current changes. The variations of the air-gap flux due to the armature slots and teeth are also very evident. Figure 11 shows the flux distribution under the pole face of a stationary direct-current motor, when the shunt field is excited. This was taken by moving the bridge element along the air gap. The oscillograph drum was rotated by a thread extending from its pulley to the bridge. Since the bridge was moved with the hand the oscillogram shows some unevenness which should not be present. Many other interesting and valuable studies could be made on stationary and running machines, as well as on other equipment.

## Directional Variations

An observation may be made here, not strictly in line with the subject at hand but nevertheless relating to an interesting and important feature of the instrument.

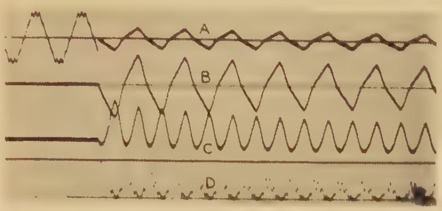

**Figure 10. Transient from no load to almost short circuit in a single-phase alternator**

A—Alternator terminal voltage
B—Alternator armature current
C—Alternator d-c field current
D—Air-gap flux under pole

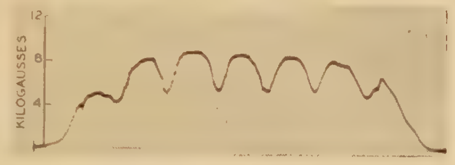

**Figure 11. Distribution of magnetic flux under the excited pole of a stationary d-c motor**

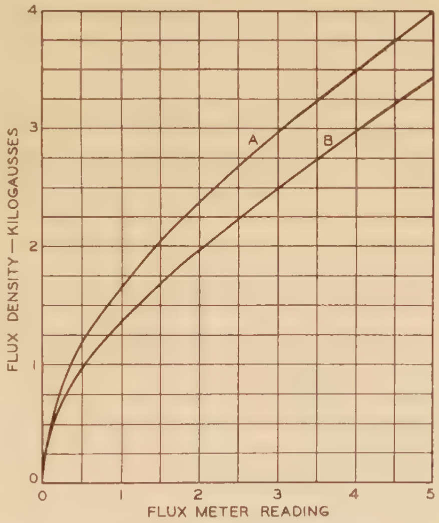

**Figure 12. Directional effect in use of magnetic fluxmeter**

Curves taken using 25 milliamperes in bridge
A—Magnetic flux parallel to plane of coils in bridge
B—Magnetic flux perpendicular to plane of coils in bridge

In the discussion on the previous paper[6] a set of curves was shown in which the bridge element was held with the plane of its coils parallel to the magnetic-flux lines. At very low-flux densities the readings were negative; at slightly higher values the negative reading decreased, finally changed to positive, and continued to increase. A greater density was always required to give the same reading than when the plane of the bridge coils was held perpendicular to the lines of flux.

By using lead or tin wire instead of nickel for the balancing resistors, no negative readings are obtained; the calibration curves obtained with the plane of the coil held parallel with the lines of flux, and also held perpendicular to the flux, are shown in figure 12. The directional effects of the magnetic field upon bismuth as well as upon other materials has been quite fully investigated in previous researches.[7]

At first thought this change might appear disadvantageous, but it has the one important advantage of indicating the resultant direction of the flux as perpendicular to the plane of the coils when the reading is maximum, or as being parallel to the plane of the coils when the reading is minimum. In the measurement and plotting of the distribution of the flux in irregular fields this indication would prove of considerable value.

## Conclusions

While this research by no means exhausts the field for study, it has definitely proved that the instrument is of value in the measurement of alternating current and transient as well as direct-current magnetic fields. Within the range studied, the frequency has no effect upon the calibration. The tendency of the bismuth resistance to lag behind the flux changes found by previous investigators has been verified, though this lag at the usual commercial power frequencies either cannot be detected or is of very low magnitude. The instrument is thus well adapted to many studies in the alternating current and transient fields.

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# Polarity Limits of the Sphere Gap

By F. O. McMILLAN
FELLOW AIEE

**Synopsis:** It is found that 60-cycle polarity characteristics correlate with the positive and negative impulse calibration curves for grounded sphere gaps sufficiently well to use them for determining the polarity limits for sphere gaps. The available data show that the maximum spacing at which a grounded sphere gap has equal positive and negative spark-over is a linear function of the size of the spheres. From this relation, it follows that the maximum sparking distance for equal positive and negative spark-over, expressed as a per cent of the diameter of the spheres, is not constant for all sphere diameters. Therefore, arbitrary polarity limits expressed in terms of the diameter of the sphere cannot apply to all sizes of sphere gaps.

EXTENSIVE use of sphere gaps in high-voltage testing and research makes it imperative to have complete data on their characteristics and limitations, particularly when the gaps are used for measuring impulse voltages. This paper describes a method of using the 60-cycle polarity characteristics for sphere gaps to determine their polarity limits of spark-over in measuring impulse voltages. Empirical expressions are derived for the equal positive and negative spark-over limit of the sphere gap in centimeters and also as a function of the diameter of the spheres. The large amount of data obtained from 60-cycle polarity characteristics and impulse tests made in the local laboratory over a period of eight years and by other investigators, have been carefully correlated in arriving at these empirical equations. As more data become available for large spheres at the higher voltages, similar expressions can be derived for the interesting but erratic transition region which is not used for high-voltage measurements. The laws proposed are applicable to the measurement of impulse voltages for which the time from zero to flashover voltage is one microsecond or more. This impulse time is the same as that for which the recommended AIEE sphere-gap calibration standards apply.

The sphere gap has been an accepted device for measuring high voltages since 1913;[1,2] however, the polarity characteristics of the grounded sphere gap were not observed until 1929. In October 1929, Lusignan[3] reported that 60-cycle symmetrical voltage only sparked over a 50-centimeter grounded sphere gap when the ungrounded sphere was negative if the spheres were one sphere diameter apart. He also reported that when the separation was 69 centimeters, spark-over occurred on both polarities.

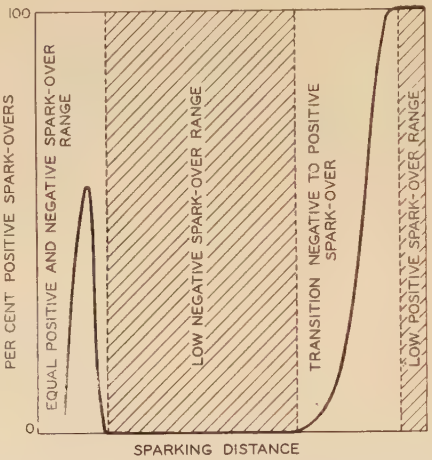

**Figure 1.** Typical 60-cycle polarity characteristic for grounded sphere gap

In 1929, during some impulse voltage investigations at Oregon State College, it was found that measurements of positive impulse voltages with grounded sphere gaps and the standard 60-cycle calibration curves gave voltage values that were too low over much of the accepted standard range of the gap.[4] This observation led to a study of the polarity characteristics of sphere gaps at 60 cycles to determine the extent and nature of the polarity effects at power frequencies. Complete 60-cycle polarity characteristics were obtained for several different types of gaps including sphere gaps. The latter showed four distinct polarity ranges occurring at different spacings of the spheres.[4]

The observed polarity characteristics of grounded sphere gaps when measuring impulse voltages were confirmed by a number of investigators, notably Allibone, Hawley, and Perry[5] in June 1933, Meador[6] in June 1934, and Bellaschi and McAuley[7] in June 1934.

General recognition of the difference in the positive and negative spark-over of grounded sphere gaps has led to extensive revision of sphere-gap calibration standards in the United States and abroad. Notable progress has been made by the AIEE subcommittee on sphere-gap calibrations in assembling positive, negative, and 60-cycle calibration data for the standard sizes of sphere gaps. Supplementing these data, it is important to know accurately the polarity limits of these gaps over a wide range of spacings. This information is readily obtained from the 60-cycle polarity characteristics, because sphere-gap polarity effects are essentially independent of the duration of the voltage wave for waves of one to two microseconds duration and longer.[8,9]

## 60-Cycle Polarity Characteristics

A typical 60-cycle polarity characteristic for a grounded sphere gap is shown in figure 1. Two methods of determining these characteristics, one utilizing visual Lichtenberg figures and the other a neon cathode-glow lamp, have been described in papers[4,6] previ-

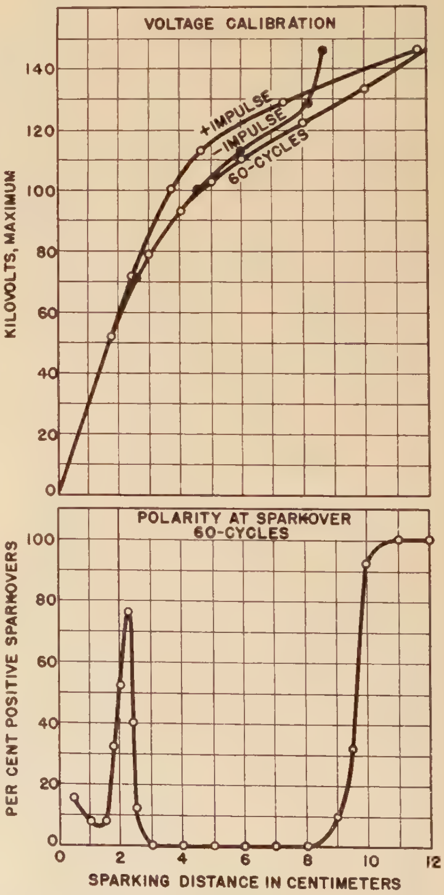

**Figure 2.** Characteristics of 6.25-centimeter grounded sphere gap

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1. For all numbered references, see list at end of paper.

ously cited. The 60-cycle polarity characteristics shown in figures 1, 2, and 3 cover a much wider range of sparking distances than are useful in measuring voltages; however, they serve to give a complete picture of the four distinct polarity ranges characteristic of grounded sphere gaps.

Both positive and negative spark-over occurs in the first range showing that the positive and negative spark-over voltages are essentially equal. The upper limit of this range is of great importance, because it shows the maximum sparking distance over which the sphere gap can be used without objectionable polarity effect.

Positive spark-over does not occur in the second range, showing that the negative spark-over voltage is less than the positive. This region is important, because it includes the remainder of the range of the sphere gap that is useful for measuring voltages and shows the spacings over which positive and negative calibrations must be used.

In the third range, both positive and negative spark-over occurs, and the gap is very erratic in its behavior, because corona forms on the ungrounded sphere at voltages that are lower than the spark-over value. This range covers the transition from 100 per cent negative spark-over to 100 per cent positive spark-over.

One hundred per cent positive spark-over occurs in the fourth range due to the formation of heavy corona streamers preceding spark-over. These corona streamers give the gap characteristics similar to those of a point-to-plane gap.

Sphere-gap spacings falling in ranges three and four are almost entirely of theoretical interest, because they have very little practical value for voltage measurements.

## Correlation of 60-Cycle Polarity Characteristics With Impulse Calibrations

When the positive and negative impulse voltage calibration curves for a sphere gap are plotted directly above the 60-cycle polarity characteristic, using a common scale of abscissas, the correlation of the 60-cycle characteristic with the calibration curves is clearly shown. This has been done for the 6.25-centimeter and 50-centimeter sphere gaps in figures 2 and 3. These sphere gaps were selected on account of the large difference in size and because complete characteristics were available. Both the 60-cycle and impulse data for the 50-centimeter gap were taken by Meador[6] in another laboratory. The wave used for the 6.25-centimeter sphere-gap impulse voltage calibration was a 1x5 microsecond wave, while the 50-centimeter gap was calibrated with a 1.5x40-microsecond wave.

Table I. Polarity Limits of Spark-Over for Grounded Sphere Gaps

| | Sphere-Gap Spacing in Centimeters and Per Cent Sphere Diameter | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Equal Positive and Negative Spark-Over Range | | | Low Negative Spark-Over Range | | | Transition Negative to Positive Spark-Over | | | Low Positive Spark-Over Range | | |
| | | Maximum | | | Maximum | | | Maximum | | | Maximum | |
| Diameter of Spheres (Centimeters) | Centimeters Minimum | Centimeters | Per Cent Sphere Diameter | Centimeters Minimum | Centimeters | Per Cent Sphere Diameter | Centimeters Minimum | Centimeters | Per Cent Sphere Diameter | Centimeters Minimum | Centimeters | Per Cent Sphere Diameter |
| 2.00 | * | | | | | | | | | | | |
| 2.54 | 0 | 2.2 | 87 | 2.2 | 3.3 | 130 | 3.3 | 3.8 | 150 | 3.8 | ∞ | ∞ |
| 6.25 | 0 | 3. | 48 | 3. | 8. | 128 | 8. | 11. | 176 | 11. | ∞ | ∞ |
| 12.5 | 0 | 5. | 40 | 5. | 15. | 120 | 15. | * | | | | |
| 25. | 0 | 9. | 36 | 9. | 30. | 120 | 30. | * | | | | |
| 50. | 0 | 13. | 26 | 13. | 50. | 100 | 50. | 70. | 140 | 70. | ∞ | ∞ |
| 75. | 0 | 22. | 29 | 22. | * | | | | | | | |
| 100. | 0 | 30. | 30 | 30. | * | | | | | | | |
| 150. | * | | | | | | | | | | | |
| 200. | 0 | 55. | 28 | 55. | * | | | | | | | |

* Limits of available data.

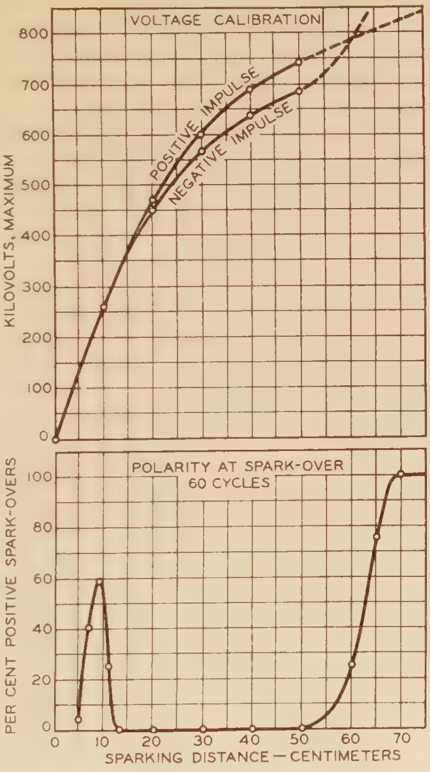


Figure 3. Characteristics of 50-centimeter grounded sphere gap

The upper limits of the equal positive and negative spark-over ranges for the two polarity characteristics coincide quite well with the points of divergence for the positive and negative impulse calibration curves. The limit for the 6.25-centimeter sphere gap is slightly higher than the branching point for its impulse calibration curves, and the limit for the 50-centimeter sphere gap is essentially coincident with the point of divergence of the calibration curves.

The range of zero positive spark-over is wider than the usual range of impulse calibration curves, and it clearly shows the gap limits over which positive and negative calibration curves must be used for impulse measurements.

The polarity characteristics shown were taken on gaps with the ungrounded sphere mounted directly above the grounded sphere and with the sparking surface of the grounded sphere four sphere diameters above the ground plane. This is the usual position of sphere gaps when making high-voltage measurements. Other 60-cycle polarity characteristics taken with the sphere gap mounted in a horizontal position with respect to the ground plane were essentially the same as those for the vertical gap except the second range over which there are no positive spark-overs was shortened, because the transition from negative to positive spark-over occurred at a shorter gap spacing.

## Polarity Limits From 60-Cycle Polarity Characteristics

Close correlation between impulse voltage calibration curves and the 60-cycle polarity characteristics makes it possible to take from the latter characteristic curves the sparking distances defining each of the four distinct polarity ranges for the different sizes of sphere gaps. The polarity characteristics at 60 cycles are readily determined if an adequate source of high voltage is avail-

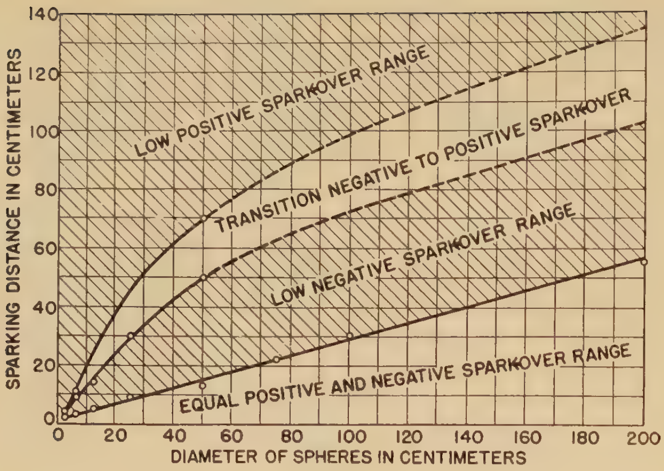


**Figure 4. Polarity limits of spark-over in centimeters for grounded sphere gaps**

able. The maximum voltage available for this investigation was limited, and hence it was necessary to draw upon data published by Meador[6] in 1934 to show the polarity limits for the large standard sphere gaps. Meador's results, which are the only data published since the original paper[4] in 1930, are the most extensive available, but they are not complete for the large sphere gaps at wide spacings.

The polarity limits of spark-over for grounded sphere gaps are shown in table I. These data are sufficient to determine the upper limit of the very important equal positive and negative spark-over range for all standard sphere gap sizes except the 2-centimeter spheres, but they are quite inadequate for the other three higher polarity ranges. It is hoped that investigators with high-voltage facilities available will extend and check the existing data.

The data in table I are shown graphically in figures 4 and 5. Figure 4 shows that the sparking distance in centimeters, marking the upper limit of the equal positive and negative spark-over range, is a linear function of the diameter of the sphere. The equation of the curve is:

$$S = 0.267\,D + 1.50 \qquad (1)$$

where

$S$ = maximum sparking distances, in centimeters, for equal positive and negative spark-over.

$D$ = sphere diameter in centimeters.

This is a very interesting and important relationship, and, if confirmed by more complete and extensive data, it shows that the more or less generally accepted idea that small sphere gaps are useful for measuring impulse voltages over a smaller per cent of sphere diameter separation than large gaps is erroneous. These data show that just the opposite is true. If the sparking distance $S$ in equation 1 is expressed as a per cent of sphere diameter $D$, the following equation may be written:

$$S_D = 26.7 + \frac{150}{D} \qquad (2)$$

where

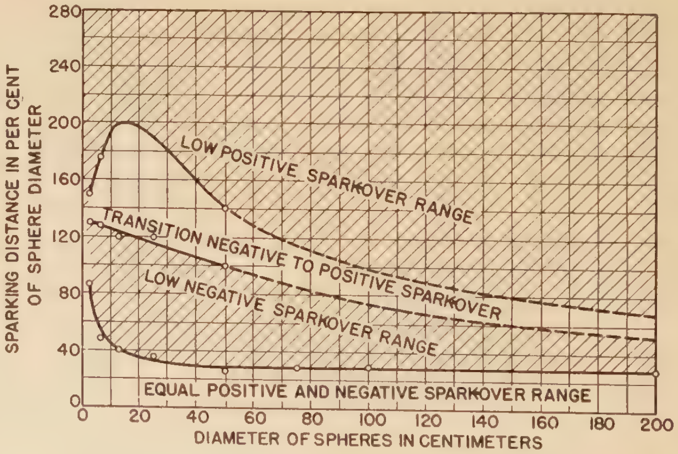
$S_D$ = maximum sparking distance, in per cent of sphere diameter, for equal positive and negative spark-over.

$D$ = sphere diameter in centimeters.

From equation 2 it is apparent that for small values of $D$ the value of $S_D$ will be relatively large, and for large values of $D$, it will approach 26.7 per cent as a lower limit.

The maximum permissible sphere-gap spacing to obtain equal positive and negative spark-over voltage within the useful range of the gap are given in table II. These are calculated values from equations 1 and 2 which give the maximum spacings in centimeters and in per cent of sphere diameter. A comparison of the calculated values in table II with the experimental values in table I shows that the agreement is well within the limits of experimental accuracy.

**Figure 5. Polarity limits of spark-over in per cent of sphere diameter for grounded sphere gaps**



Reference to the experimental values in table I shows that the 2.54-centimeter sphere gap shows no appreciable polarity effect until a spacing of 87 per cent of sphere diameter is reached, while the 200-centimeter gap shows a polarity effect at 28 per cent of diameter separation. The maximum sparking distances for equal positive and negative spark-over, expressed in per cent of sphere diameter, are shown graphically in figure 5.

In the light of these data, it is not advisable to establish arbitrary sphere-gap limits expressed in terms of sphere diameter and apply them to all gaps regardless of size, as has been the practice in previous standards for measuring high voltage.

The boundary curves for the low negative spark-over range and the transition from low negative to low positive spark-over are only reasonably well established up to 50-centimeter diameter spheres; beyond that point the curves are located entirely by extrapolation without adequate data, and the curves may be very much in error. These portions of the sphere-gap characteristics are beyond the limits that are useful for measuring voltage, but it is believed when data are available to establish them accurately, they will assist in obtaining a better understanding of sphere-gap characteristics within the useful range. The available data show that as sphere gaps increase in size, the polarity limits do not increase to the proportions that would be expected. This may be due, at least in part, to abnormal flux distortion because of inadequate free space around the large gaps.

When important measurements are to be made, a low-frequency polarity characteristic may be taken on the sphere gap in position to determine whether or not the polarity characteristics are normal. This precaution is important with large gaps, because it is a well-known fact

**Table II. Maximum Sparking Distance for Equal Positive and Negative Spark-Over Voltage for Grounded Sphere Gaps**

Values Calculated From Empirical Equations

| Diameter of Spheres Centimeters | Maximum Sparking Distance<br>Centimeters<br>$S = 0.267D + 1.50$ | <br>Per Cent Sphere Diameter<br>$S_D = 26.7 + \frac{150}{D}$ |
|---|---|---|
| 2.00 | 2.03 | 101.7 |
| 2.54 | 2.18 | 85.7 |
| 6.25 | 3.17 | 50.7 |
| 12.5 | 4.84 | 38.7 |
| 25. | 8.18 | 32.7 |
| 50. | 14.9 | 29.7 |
| 75. | 21.5 | 28.7 |
| 100. | 28.2 | 28.2 |
| 150. | 41.5 | 27.7 |
| 200. | 54.9 | 27.5 |

that the flux distortion due to the ground plane causes the polarity effect, and when this distortion is abnormal, standard calibration data no longer apply.

## Concluding Summary

1. The 60-cycle polarity characteristics for grounded sphere gaps show four distinct polarity ranges:

I. Equal positive and negative spark-over.

II. Low negative spark-over.

III. Transition from low negative to low positive spark-over.

IV. Low positive spark-over.

2. The correlation of the 60-cycle polarity characteristics with the positive and negative impulse voltage calibration curves for grounded sphere gaps is such that the 60-cycle polarity characteristics may be used to determine the impulse polarity limits for measuring voltage waves that increase from zero to flashover in one microsecond or more.

3. All available data show that the maximum sparking distance for equal positive and negative spark-over is a linear function of sphere diameter over the entire range of standard sphere-gap sizes. The equation for the relationship is:

$$S = 0.267\,D + 1.50$$

4. Small grounded sphere gaps may be used over a greater per cent of diameter separation than large gaps without appreciable polarity effect.

5. The maximum sparking distance for equal positive and negative spark-over voltage for grounded sphere gaps, expressed as a per cent of the diameter of the spheres, is a variable function of the sphere diameter. The equation for the relationship is:

$$S_D = 26.7 + \frac{150}{D}$$

Therefore, it is inadvisable to establish arbitrary sphere-gap polarity limits expressed in terms of sphere diameter and apply them to all gaps regardless of size.

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3. A Study of High Voltage Flashover, J. T. Lusignan, Jr. AIEE Transactions, volume 48, 1929, pages 246–254.

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## Discussion

**J. R. Meador** (General Electric Company, Pittsfield, Mass.): This is an interesting continuation of the work reported by the author and E. C. Starr in 1931.

I wish to comment on the statement:

> The available data show that as sphere gaps increase in size, the polarity limits do not increase to the proportions that would be expected. This may be due, at least in part, to abnormal flux distortion because of inadequate free space around the large gaps.

The implications of this statement are important to those who expect to use sphere gaps over a wide range of gap spacings.

In the tests reported in the writer's paper ("Calibration of the Sphere Gap," J. R. Meador, AIEE Transactions, volume 53, 1934, pages 942–8) it was found that the transition points from partial negative spark-over to all negative spark-overs (usually near one-fourth diameter spacing) and from all negative spark-overs to partial negative spark-overs (usually near diameter spacing) were not entirely consistent. This was particularly true of the $6^1/_4$-centimeter sphere gap which had no all-negative spark-over range.

In the early part of 1934 the writer made a few tests on several sizes of spheres to determine the effect of surroundings on the spark-over voltage and polarity characteristics. Some of the results obtained may be of interest.

With $6^1/_4$-centimeter spheres at $6^1/_4$-centimeter spacing and the sparking point of the grounded sphere 4.1 diameters above a flat grounded plate, 100 per cent negative spark-overs were obtained. When the spacing above ground was increased to 5.7 diameters, only 80 per cent of the spark-overs were on the negative half cycle. With four vertical line-potential wires spaced ten inches from the center line of the spheres, the voltage was approximately the same as without shielding wire but all spark-overs were positive polarity. In this case the spheres were overshielded.

Similar effects of shielding were obtained with the 12.5-centimeter and 50-centimeter spheres. In each case when the shielding wires were adjusted to give equal positive and negative spark-overs, the 60-cycle calibration curve was in close agreement with the calculated curve for isolated sphere gaps. Similarly, the positive and negative polarity impulse spark-over curves were practically the same.

These comments are made to emphasize the fact that care must be exercised when the spheres are used at spacings above $^1/_4$ to $^1/_8$ of diameter for either low frequency or impulse measurements, since the surroundings may appreciably influence the polarity characteristics and consequently the spark-over voltage on both polarities.

**Abe Tilles** (University of California, Berkeley): Professor McMillan's most interesting paper presents, logically assembled, a great deal of useful information. It answers numerous questions and raises still other questions.

In the so-called "equal positive and negative sparking range" of figures 1, 2, and 3 would it not be more correct to alter the nomenclature somewhat? Possibly "range of spark-over of both polarities" would do. The curve seems to have a definite structure in that range and there seem to be strictly "equal" spark-overs only where the curve is, within the limits of error, at an ordinate of 50 per cent. How well defined is the curve in that region? How many individual spark-overs is it necessary to observe to establish a point on this curve?

In comparing the 60-cycle polarity curves of figure 3 for 50-centimeter spheres and of figure 2 for 6.25-centimeter spheres an upturn is observed at the smallest spacings of figure 2. Presumably, for such a curve on the still smaller 2.5-centimeter spheres, and for measurements at still smaller spacings, this upturn might be observable in greater detail. It would be of interest if Professor McMillan could publish such a curve for the smallest spheres and spacings at which he obtained data. Small gaps may show interesting differences in behavior from large gaps.

It is clear, I believe, that any appreciable even harmonic distortion in the voltage wave shape would introduce error into the results. In what way, and to what degree of refinement, was the voltage wave shape controlled or observed?

In assembling these data Professor McMillan has doubtless had occasion to consider what varying mechanisms of spark-over account for the different "polarity ranges" at different spacings. It would be helpful if he would care to state more fully what he considers these mechanisms of spark-over to be.

**D. W. VerPlanck** (Yale University, New Haven, Conn.): As pointed out by Professor McMillan the negative impulse spark-over voltage for grounded sphere gaps is lower than the positive at intermediate spacings but becomes higher at large spacings. From this, one might expect that with alternating voltage in the intermediate range of spacings, all spark-overs would have negative polarity, and that at the spacing where the impulse characteristics cross, the polarity of the alternating voltage sparks would change abruptly from negative to positive. Actually, however, as shown in the paper, the transition from negative to positive polarity is a gradual one extending over a range which includes the spacing at which the impulse characteristics cross (see figures 2 and 3). That the transition is not abrupt may possibly be because of an insufficient continuous supply of initiating electrons in critical parts of the gap. In this connection it would be interesting to know whether or not McMillan's data were obtained from tests on irradiated gaps.

While the middle of the transition range may be at the spacing where the impulse characteristics cross, the transition appears to begin, as will be shown below, at the spacing for which the ratio of positive to negative impulse voltage is a maximum.

The ratio of positive to negative impulse spark-over voltage as a function of spacing to diameter ratio for the various standard sphere sizes is plotted in the figure accompanying this discussion. These curves, obtained with the aid of empirical formulas presented in a recent paper ("A New Correlation of Sphere-Gap Data," D. W. VerPlanck, AIEE TRANSACTIONS, January 1938, page 45) are in accord with the revision of the AIEE proposed sphere-gap standards dated December 1937. The dashed portions of the curves are extrapolations by means of the formulas beyond the region actually covered by the standards. The maxima of these curves occur at spacing to diameter ratios shown in table I of this discussion, which increase with decreasing sphere diameter. An examination of Professor McMillan's figure 5 shows that the lower boundary of his transition region occurs at spacing to diameter ratios, also shown in table I, which are substantially the same as those for the maximum ratio of positive to negative impulse voltage. Thus independent evidence is presented confirming Professor McMillan's results at least to the extent of showing that there must be some change in the mechanism of sparking commencing at about the spacing to diameter ratios shown in table I.

Another, though less definite check is that each of the curves showing the ratio of positive to negative impulse spark-over voltage has a point of inflection at roughly the same spacing to diameter ratio as the lower boundary of the "low negative spark-over range" in Professor McMillan's figure 5. This may indicate another change in the character of the spark discharge.

**Table I**

| Sphere Diameter (Centimeters) | Spacing to Diameter Ratio: For Maximum Ratio of Positive to Negative Impulse Spark-over Voltage | For Beginning of Transition Negative to Positive Spark-over Polarity |
|---|---|---|
| 200 | 0.55 | 0.55 |
| 150 | 0.65 | 0.60 |
| 100 | 0.80 | 0.75 |
| 75 | 0.87 | 0.85 |
| 50 | 1.0 | 1.0 |
| 25 | Greater than 1.0 | 1.15 |

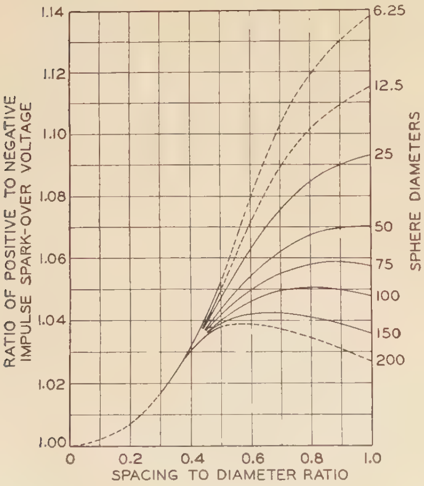

Figure 1

**F. O. McMillan:** It is suggested by Professor VerPlanck that the rather gradual transition from negative to positive spark-over may be due to an insufficient continuous supply of initiating electrons in critical parts of the gap, and he asks whether the data were obtained from irradiated gaps. The gaps were not irradiated to obtain any of the data used, hence the initiating electrons were supplied entirely by the normal ionization of the air in the interelectrode space. Some experimental evidence at hand indicates that the number of ions present does influence the polarity characteristics near the transition regions. However, it is believed that the rather long transition range between negative and positive spark-over is largely due to the fact that it occurs over the range of gap spacings where the corona discharge and spark-over curves are diverging. When corona occurs at a slightly lower voltage than complete spark-over, voltage disturbances are set up by the corona that cause spark-over to occur on both polarities. As the gap spacing is further increased and the voltage difference between corona formation and spark-over becomes greater, the corona streamers on the ungrounded sphere reach sufficient length to cause the gap to behave somewhat like a point-to-plane gap, and the spark-over always occurs when the ungrounded sphere is positive.

The graphs of the ratio of positive to negative impulse spark-over voltage as a function of spacing to diameter ratio obtained by Professor VerPlanck from his recently developed formulas for sphere-gap characteristics lead to conclusions that agree remarkably well with the data in the paper. This independent evidence aids materially in establishing the dependability of the results.

A question of nomenclature is raised by Doctor Tilles. He suggests "range of spark-over of both polarities" in place of "equal positive and negative spark-over range." Whether or not this is desirable depends upon the quantities to which "equal" is applied. If an equal number of positive and negative spark-overs is understood, the point is well taken; however, the expression is used in the paper to state that the magnitudes of the positive and negative spark-over voltages are essentially equal for the range in question. This use is believed to be justified because if both positive and negative spark-overs occur at a given spacing, even though they are unequal in number, the magnitudes of the positive and negative spark-over voltages must be essentially equal within the limits of measurement, otherwise spark-over would occur only on one polarity.

The ordinates of the polarity characteristic curves for the range of gap spacings in question are determined by the laws of probability and are established by taking a relatively large number of observations at each point. Usually 25 to 50 observations will locate a point reasonably well, but in most instances a hundred or more observations were made to determine each point on the polarity characteristics.

The 60-cycle polarity characteristics for different sizes of grounded sphere gaps all show four distinct polarity ranges as described in the paper, but the relative widths of the ranges vary with the size of the spheres as shown by the curves in figure 5. The upward inflection of the 6.25-centimeter sphere-gap polarity characteristic at close spacings is characteristic of small gaps and is exhibited to an even greater degree by the 2.54-centimeter sphere gap. The polarity characteristic curve for a 2.54-centimeter sphere gap is shown in figure 9 of the paper "The Influence of Polarity on High-Voltage Discharges," AIEE TRANSACTIONS, volume 50, page 25.

As Doctor Tilles points out, even harmonic distortion of the 60-cycle voltage wave shape would introduce errors in the results. This was guarded against by using an alternator with a good wave form, by using field control on the alternator to vary the voltage, and by the careful elimination of all voltage-distorting phenomena such as nonlinear circuit elements and corona discharges.

A gap that is physically and electrically symmetrical does not show any polarity effect. The mechanism of spark-over for each of the four polarity ranges of the grounded sphere gap can, therefore, be accounted for reasonably well by the dielectric flux distortion due to the ground plane and its resulting influence on the ionization phenomena in the gap.

Consider a grounded sphere gap mounted perpendicular to the ground plane with the spark gap four to five sphere diameters above it, and the lower sphere connected electrically to the plane. When voltage is applied to such a gap, a dielectric field is established between the insulated and the grounded sphere and also between the insulated sphere and the ground plane.

At relatively close spacings, the flux between the sparking surfaces of the spheres is not appreciably distorted by the ground plane; hence, the voltage gradients at the sparking surfaces of the two spheres are equal and the gap does not show any polarity effect.

When the sparking distance is increased beyond a certain value, which the paper shows to be a function of sphere diameter, the ground plane distorts the dielectric field between the spheres to such an extent that the gap becomes electrically unsymmetrical and a polarity effect results. A part of the flux originating on the insulated sphere terminates on the grounded sphere and a part of it on the ground plane. Because of this flux distribution, the flux density and the resulting voltage gradient is greater on the sparking-surface of the upper ungrounded sphere than on the lower grounded sphere. When the gap spacing is further increased, the flux distortion and the difference in voltage gradient at the sparking-surfaces of the two spheres becomes greater.

When the top sphere is negative, the electrons in the gap are repelled from it toward the bottom grounded sphere. If the voltage gradient is sufficiently high, these electrons will attain ionizing velocities and release more electrons and positive ions by ionizing the air. The newly formed electrons are also repelled and produce further ionization as they travel toward the positive grounded sphere. The original positive ions in the gap and those formed by the avalanche ionizing action are attracted toward the negative sphere, but due to their relatively large mass and resulting low velocity, as compared with the electrons, a positive space-charge results. The maximum ionization and, therefore, the maximum positive space-charge will occur in the region of highest voltage gradient or near the ungrounded negative sphere. This positive space-charge near the negative sphere further increases the gradient and the ionization in that region. As the positive space-charge approaches very near the negative sphere, it probably ultimately produces a sufficiently high gradient to overcome the work function of the metal and extracts electrons from the sphere. Some of the electrons extracted recombine with positive ions, and others are projected into the interelectrode space and sustain the ionization. This ionization process progresses until the entire distance between electrodes is ionized, and spark-over occurs if the spacing of the sphere gap is within the range where the corona-formation voltage and spark-over voltage are identical. Reversing the polarity of the sphere gap, the upper ungrounded sphere becomes positive, and the region of high-voltage gradient resulting from the flux distortion of the ground plane is on the upper sphere as before. The electrons and negative ions are attracted to the top sphere, and the positive ions left behind by the avalanche process of ionization by collision are near the ungrounded sphere as before, but it is now positive instead of negative. Under these conditions, the grounded negative sphere must supply the electrons for sustaining a discharge between spheres. However, the negative sphere has a low voltage gradient at its discharge surface due to the ground-plane flux distortion, and the further fact that the point of maximum positive space-charge is at the point of maximum ionization near the positive sphere. As a result of these conditions, the extraction of the necessary electrons from the negative sphere to sustain a discharge requires a higher voltage when the upper ungrounded sphere is positive than when it is negative. Therefore, at intermediate gap spacings where both corona formation and spark-over occur at the same voltage, the grounded sphere gap sparks over at a lower voltage when the upper ungrounded sphere is negative than when it is positive.

At wide gap spacings, where corona forms on the ungrounded sphere of the grounded gap at a voltage lower than the spark-over value, the characteristics of the gap are materially altered. Under these conditions the sphere gap takes on the characteristics of a gap having electrodes with a very marked dissimilarity. The corona streamers on the top sphere act as points and the bottom sphere and ground plane as a composite electrode. The condition is a compromise between a point-to-sphere and a point-to-plane gap. When the ungrounded sphere is positive, the free electrons are attracted upward toward it and accelerated to the ionizing velocity in the region where the voltage gradient is sufficiently high. These electrons and those liberated by ionization, except the ones lost by recombination, are conducted away by the positive electrode. The relatively immobile positive ions not neutralized by recombination are left along the ionization or corona-streamer paths and form space charges. These positive space charges add to the field from the positive electrode and extend the ionizing gradient at the ends of the streamers to greater distances. In this manner ionization is progressively extended downward at the ends of the corona streamers until either the gradient at the extreme limit of the ionized region falls below the critical value or complete spark-over occurs. When the ungrounded sphere is negative, the free electrons in the surrounding space are repelled downward at high velocity producing ionization by collision in the region that is above the critical gradient. A positive space charge is formed near the negative sphere, and a negative space charge is formed outside of the positive space charge. The field of the positive space charge opposes the field from the negative electrode which it surrounds and reduces the resultant electrode flux in the area outside of the positive space charge. The decrease of flux due to the positive space charge around the negative sphere reduces the distance to which the ionizing gradient extends from the electrode and hence increases the voltage necessary to cause complete spark-over. Therefore, at wide spacings on the grounded sphere gap where corona occurs at an appreciably lower voltage than complete spark-over the gap sparks over at a lower voltage when the ungrounded sphere is positive than when it is negative.

J. R. Meador in his discussion further stresses the importance of adequate clearance around sphere gaps to avoid abnormal flux distortion and the resulting erratic characteristics. That point cannot be emphasized too strongly, because there is no doubt that it is the cause of much difficulty with sphere-gap measurements.

The inconsistencies in the transition from partial negative spark-over to all negative spark-overs found by Mr. Meador in his 1934 investigations, which he points out were particularly pronounced in the case of the 6.25-centimeter sphere gap, merit special consideration. In contrast with Mr. Meador's experience, we have always obtained polarity characteristics for the 6.25-centimeter sphere gap that show consistently a definite range of gap spacings over which the spark-over is 100 per cent negative.

The change from 100-per-cent-negative spark-overs to 80 per cent, when the sparking point of the ground sphere was raised from 4.1 sphere diameters to 5.7 sphere diameters above the ground plate, reported by Mr. Meador, probably is not due to the change in position of the gap with respect to the ground plane.

During the academic year 1933–34, E. D. Harrington and K. M. Klein, students at Oregon State College, made a careful investigation of the influence of the ground-plane position on the polarity characteristics of the 6.25-centimeter sphere gap. The results of their investigations were given in a paper presented before the Portland Section of the AIEE on May 19, 1934. They used a vertical gap with the sparking surface of the grounded sphere at various distances ranging from 1 to 20 diameters above a large metal ground plate. The polarity characteristics, over this entire range of ground-plate positions, each showed a definite range of gap spacings over which the spark-overs were 100 per cent negative. The 100-per-cent-negative spark-over range was changed to some extent by the position of the ground plane, but typical polarity characteristics with four distinct polarity ranges were obtained for all ground-plane positions.

In 1935, polarity characteristics were taken for a 6.25-centimeter horizontal grounded sphere gap. The characteristics were taken with the horizontal axis of the spheres at both four and five diameters above the ground plane. This horizontal gap also had typical polarity characteristics with the usual four distinct polarity ranges.

For the past eight years, the polarity characteristic of either a 6.25-centimeter or a 12.5-centimeter vertical sphere gap has been taken each year by students as a high-voltage laboratory experiment. These polarity characteristics have always shown a 100-per-cent-negative spark-over range and have been typical in every respect.

In view of this evidence, we are forced to the conclusion that Mr. Meador's failure to find a range over which the spark-over of the 6.25-centimeter gap was 100 per cent negative was due to some extraneous cause not directly related with the polarity characteristics of the gap.

It has been found that it is necessary to have the circuit free from corona discharges of any magnitude when the polarity characteristics are taken on small sphere gaps. The elimination of corona is important because corona discharges cause transient disturbances in the voltage that alter the polarity distribution of spark-over on small gaps. It is possible that either corona or some other electrical disturbance may account for Mr. Meador's failure to secure any 100-per-cent-negative spark-over range on the 6.25-centimeter sphere gap.

The shielding effects of wires reported by Mr. Meador are very interesting and are in agreement with the results obtained by George M. Chandler in his thesis "The Control of Sphere-Gap Polarity Characteristics" submitted at Oregon State College in 1935. Mr. Chandler used one toroidal shielding ring around the upper ungrounded sphere and in various vertical positions with respect to it, and also two toroidal rings with one around each sphere of the gap. He found that one shielding ring properly adjusted around the ungrounded sphere was adequate to eliminate the polarity effect.

# Devices for Controlling Amplitude Characteristics of Telephonic Signals

By A. C. NORWINE
NONMEMBER AIEE

**Synopsis:** This paper describes a family of devices which automatically respond to signals and control the circuit amplification in such a way as to improve transmission. Their general characteristics are outlined, their differences explained, and some of their applications are listed.

THE transmission of speech energy over electrical circuits is attended by the interesting and sometimes difficult problem of preserving the original signal in spite of limitations in the transmission medium. These limitations include load-carrying capacity, interference with other service, noise, change in attenuation with time, and many others. Because of special limitations it is sometimes desirable to alter the amplitude characteristics of the speech or other signal energy without, of course, materially lowering its intelligibility. In high-quality systems the peak voltage from some speech sounds of a given talker may be over 30 decibels (some 30 times) higher than from his weakest sounds when there is very little inflection in the speech. Loudness changes for emphasis will increase this range of intensities. Ordinary message systems do not have to contend with quite so wide a range of instantaneous voltages from a single talker, but different talkers under extreme terminal conditions produce about a 45-decibel range of average voltage, which is additive to that for a single talker. Consequently, a voltage range of about 70 decibels (over 3,000 to 1) must be considered for message circuits.

In order to accommodate such ranges of intensity to certain transmission media such as radio links a new family of automatic devices has been developed. In general all of these contain amplifiers or attenuating networks whose loss or gain is changed according to some function of the applied input and which may have a variety of time sequences in their control circuits. It is hoped that by the classification and description of some of these devices their distinguishing characteristics and fields of usefulness will be made somewhat clearer. We are to be concerned here principally with those elements allied to the telephonic art, although some applications are to be found in other fields. It is not intended to include those voice-operated functions which are essentially switching operations although the distinction in some cases becomes exceedingly fine.

Names of volume-controlled devices[*] which have been used in published papers include vogad,[†][2–4] compandor,[**][5,6] and volume limiter.[7] Without direct comparison it may not be obvious how these and similar devices differ. First the apparent similarity of several of these devices will be shown in simple diagrams. Next the more important characteristics of a number of devices will be presented in tabular form, followed by descriptions of the different types. These will then be discussed with particular emphasis on their distinctive qualities, with notes on their variants which have some apparent value.

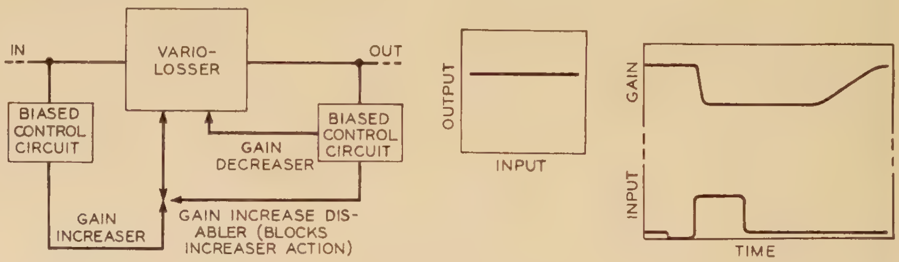

Figure 1. Vogad

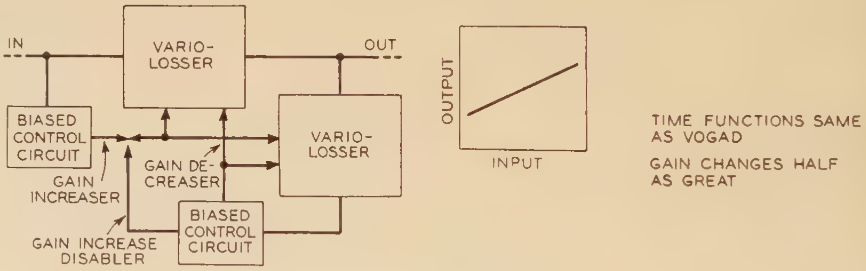

Figure 2. Half vogad

## General Characteristics of Volume-Controlled Devices

In figures 1 to 10 are shown simplified diagrams of some of these devices. While detailed descriptions of them will be deferred till later it may be pointed out that all those shown contain "vario-lossers," and all have paths from the main transmission path to control circuits which affect the vario-losser. A vario-losser usually consists of a balanced pair of vacuum tubes whose gain is changed by varying the grid bias or a network of nonlinear elements such as copper oxide or silicon carbide whose loss is changed by varying a current through them. In some special cases it may be a mechanically adjusted variable network. The word "vario-losser" is thus a generic term relating to a circuit whose loss or gain is controllable. A control circuit ordinarily consists of an amplifier and rectifier whose d-c or a-c output bears a chosen relation to its input. Thus some control circuits are marginal; they produce no control voltage till the input exceeds some critical value, then produce large control voltages for small additional increments of input. These are used, for example, when it is desired to limit the output of a vario-losser to a definite amount. Another type of control circuit produces a current or voltage which is linear with input expressed in decibels. In combination with a vario-losser whose gain is a linear function of control current or

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2. For all numbered references, see list at end of paper.

[*] See the footnote on page 63.

[†] "*Vo*lume-operated *ga*in-adjusting *d*evice."

[**] A combination of the names *comp*ressor and exp*andor*.

Table I—Characteristics of Volume-Controlled Devices

| Device | Gain Controlled by | Frequency of Adjustment | Time Required for Gain Changes: Gain Increase | Time Required for Gain Changes: Gain Reduction | Ratio of Output Range to Input Range** | Position of Controls | Volume Range Controlled* | Frequency Range Controlled | Frequency Range Causing Control | Part of Input Range Causing Operation |
|---|---|---|---|---|---|---|---|---|---|---|
| 1. VOGAD | Average volume | Infrequent. Gain fixed between transmissions | After a few words—sometimes eight to ten words | After one or more words | Approximately 0 | At input and output | Large | Full band transmitted | Full band | All |
| 2. VOLUME LIMITER | Average volume over part of input range | Relatively infrequent. Approaches maximum gain in silent periods. | Slow and continuous | After one or more words | 1 up to operate point. 0 above | At output | Moderate | Full band | Full band | High amplitude only |
| 3. COMPANDOR<br>a. Compressor<br>b. Expandor | Syllabic variations | Continuous at syllabic rate | On each syllable | On each syllable | 1/2 to 1/5<br>5 to 2 | Compressor output<br>Expandor input | Large | Full band | Full band | All |
| c. Special compandor | Syllabic variations | Continuous at syllabic rate | On each syllable | On each syllable | 1/2 to 1/5<br>5 to 2 | Compressor output expandor input or expandor control over separate channel | Large | High frequency only or multi-band | High frequency only or multi-band | All or high amplitude only |
| 4. RADIO-NOISE REDUCER (Limited-range expandor) | Syllabic variations over part of input range | Each syllable | On each syllable | On each syllable | 2 for low amplitudes. 1 for high. | At input | Moderate | Full band | Full band | Variable at low amplitudes only. Fixed gain to high amplitudes |
| 5. LIMITED-RANGE COMPRESSOR | Syllabic variations over part of input range | Each syllable within the operating range | Fast | Fast | 1 up to operate point, then 0 to 1/2, then 1 | At input or output | Small | Full band | Full band | High or intermediate amplitudes |
| 6. PEAK LIMITER | Syllabic peaks | Infrequent | After about one word | On single syllable | 1 up to operate point, then approaches 0 | At output | Small | Full band | Full band | High amplitude only |
| 7. PEAK CHOPPER | Instantaneous peak voltage | Relatively infrequent | Instantaneous | Instantaneous | 1 up to operate point then 0 | At input | Very small | Full band | Full band | High amplitude |
| 8. CROSS-TALK SUPPRESSOR | Voltage exceeding a specified value low in input range | Relatively frequent | Fast | After one or two words | 1 except at point of discontinuity | At input | Very small | Full band | Full band | All above specified low value |
| 9. ROOTER AND INVERSE ROOTER | Instantaneous voltage | Continuous | Instantaneous | Instantaneous | Ordinarily 1/2 and 2 | Integral with vario-losser | Moderate | Full band | Full band | All |

* Outside these ranges most of the devices tend to be linear transducers except for higher volumes applied to "limiters."
** It is important to note that these ranges are measured in the same units as the respective control circuits measure: *viz.*, "volume," "syllabic power," "voltage," etc.

voltage one can produce a device whose gain is a linear function in decibels of the input to the control circuit.

It will be recognized that if the application or removal of the control energy is retarded, the action of the control circuit may be made quite different on transient inputs than on steady-state inputs. It will appear later that this is the important distinction between some of the devices to be discussed and that fundamental differences in their functioning are thus brought about.

Referring to the figures once more it will be noted that some control devices are connected to the transmission path at the input to the vario-losser. These are known as "forward acting" control circuits. Other controls, connected at the vario-losser outputs, are known as "backward acting" control circuits. This is simply convenient terminology to indicate whether the control energy is progressing in the same direction as the main transmission or is progressing in a backward direction after traversing the main path, usually through a vario-losser. Some backward-acting controls function to measure the output of the devices containing them and to make whatever adjustments are required. Others are placed in that position to take advantage of the vario-lossers in the transmission paths, i.e., such controls could be replaced by combinations of forward-acting controls and extra vario-lossers.

In table I, nine of the volume-controlled devices* which have been developed for various commercial and experimental uses are listed with the functions of voltage, time, and frequency which are employed to obtain their respective performances. There is, of course, some latitude in the choice of these functions for any one device. Pending more complete description of the different types in the following paragraphs this table should be viewed as illustrating the general character of the different circuits and also the range of the variables which already have been employed. For example, it will be seen that instantaneous voltage of the signal wave, its short-time average value, peak power, syllabic variations, and long-time average power have all been used as criteria of gain settings in different circuits. Some devices change their adjustments only when critical values or ranges are exceeded, while others vary somewhat with every syllable if speech, for example, is being transmitted. Some are linear transducers to all but low or high amplitudes while others reduce or increase the output range from that at the input. It will be seen that proper choices of times for gain increase and gain decrease in combination with certain gain-control criteria make possible a wide variety of signal-altering means to meet different requirements.

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* The names employed do not follow an entirely logical classification, but they are given here because they have had considerable usage. For the same reason the term "volume-controlled devices" is used, although to be strictly correct it might better be "sound-energy-controlled devices," for example, for not all the devices operate in accordance with "volume" as measured by the well-known class of visual-reading meters called "volume indicators."

## Description of Devices in Table I

With this introduction to the combinations of characteristics which are possible it should be less difficult to distinguish between the specific devices discussed in the following paragraphs, which in addition to describing the devices, contain some comments which should assist in visualizing their forms and their operation.

1. The *vogad* (figure 1) is a device which will maintain at its output speech volume[1] which, over a certain range of input, is relatively independent of the speech volume applied to its input and which, in the ideal case, will not change its gain during periods of no speech input. It makes little or no alteration in the ratios of maximum and minimum instantaneous-to-average voltages of the speech.

2. The *volume limiter* (figure 3) is a device which is a linear transducer for all speech volumes up to a critical value, beyond which all input volumes produce essentially the same output volume. It is essentially different from the vogad in that its gain approaches the maximum value when input is removed.

3. The *compandor* (figures 4 and 5) is composed of a *compressor* and an *expandor*. A *compressor* is a device whose input-output characteristic on a decibel scale has a slope less than unity* and whose gain or loss is variable under control of the input energy at a time rate which will permit it to follow the syllabic rate of change of speech energy. Similarly, an *expandor* is a device whose input-output curve has a slope greater than unity and whose gain is variable at a syllabic rate under control of the input energy. Thus very shortly after all input is removed the gain of a compressor is maximum and the loss of an expandor is maximum. The reciprocal of the compressor characteristic slope is spoken of as the compression ratio, and the slope of the expandor characteristic is spoken of as the expansion ratio.

4. The *radio noise reducer*[8,9] (figure 6) combines the functions of an expandor which operates in the range of amplitudes where noise and weaker speech sounds lie and a linear transducer which comes into play for all amplitudes exceeding a critical value, which can be set to best suit the atmospheric noise conditions. In other words, the radio-noise reducer is a limited-range expandor. Inputs which are below the expandor range are subject to transmission at the minimum gain.

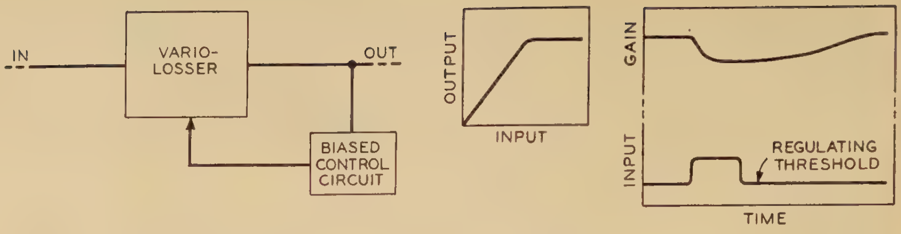

Figure 3. Volume limiter

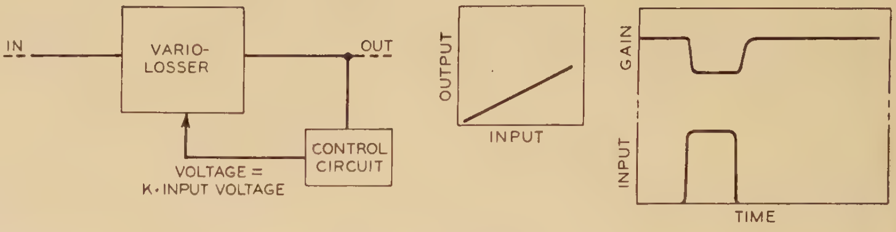

Figure 4. Compressor

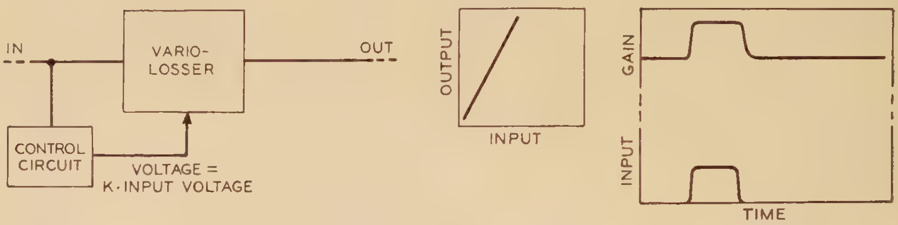

Figure 5. Expandor

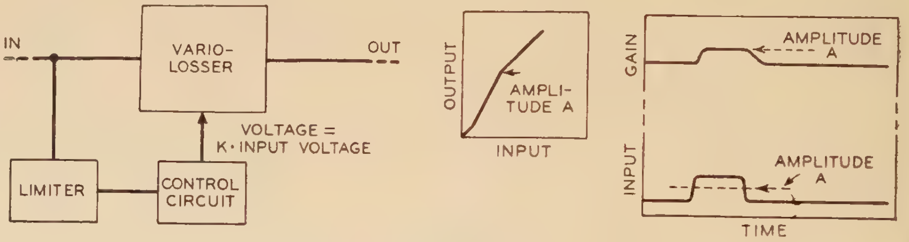

Figure 6. Limited-range expandor

Radio-noise reducer

5. The *limited range compressor* (figure 7) is a device whose operating range includes a region within which compression at a syllabic rate can take place; at other inputs the device is a linear transducer. Its connecting diagram and time functions are the same as those shown in figure 5 except that the control circuit contains a limiting device, so that compression takes place in only a portion of its input range, analogous to the action of the limited-range expandor of figure 6. As a special case the *limited range compressor* may have no linear range above its compression range, thus becoming one type of peak limiter.

6. The *peak limiter* (figure 8) is a device whose gain will be quickly reduced and slowly restored when the instantaneous peak power of the input exceeds a predetermined value. The amount of gain reduction is a function of the peak amplitude, and in practice is usually intended to be small to prevent material reduction of the range of intensity of the signal.

7. The *peak chopper* (figure 9) is a device which prevents transmission of peak amplitudes exceeding a critical amount, an essential characteristic being that the loss it inserts is completely determined by the instantaneous voltage of the signal; that is, its operating and releasing times are substantially equal to zero.

8. The *cross-talk suppressor* (figure 10) is a device which normally presents a prescribed loss to transmission, which loss is removed rapidly when the input amplitude exceeds a certain threshold and is reinserted at a definite time after the input is removed. It reduces low-amplitude unwanted currents such as cross talk but does not affect amplitudes in the useful signal-voltage range. This device differs from the limited-range expandor in that the time during which the low-loss condition is maintained is considerably greater, so the transition from one gain to the other occurs less frequently.

9. A *rooter* is an instantaneous compressor. Such a circuit can be made to produce an output whose instantaneous voltage is, for example, the square root or some similar function of the instantaneous voltage applied to the input. An *inverse rooter* is an instantaneous expandor whose characteristic is complementary to that of the rooter. A combination of *rooter* and *inverse rooter* will reduce the load requirements on a trans-

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* That is, if the input increases by $x$ decibels the output increases by less than $x$ decibels.

mission system between the two units but requires that it transmit a wider band of frequencies than that for the original signal, and that it be essentially free from phase distortion. This does not seem to be an attractive arrangement from a commercial viewpoint and is included here simply as an illustration of one of the possible modifications of signal energy. It is not shown in the group of diagrams.

## Variants to the Devices Described

In addition to these there are various devices which are essentially modifications of those described. For example, a half vogad, figure 2, may have the same time functions as a vogad, figure 1, but the gain changes in the transmission circuit are half as great for the same range of input volumes. Thus in a vogad the range of gain changes in the transmission circuit is equal to the range of input volumes, so that the output volume is the same for all input volumes. In the case of the half vogad the range of gain changes in the transmission path is one-half the range of input volumes, so the output volume range is one-half that of the input. It is also possible to construct a vogad whose output volume range is any desired fraction of the input range. As another example of modification of the devices described, for special applications it may be desirable to incorporate a certain amount of syllabic compression in a vogad.

Communication circuits which have separate paths for oppositely directed transmission between the two terminals are usually operated at such an over-all loss that with ordinary terminations there will be little tendency for circulating currents to build up to a "singing" condition. Sometimes there may not be a great deal of margin, however, so that volume-controlled devices added to such circuits must add loss at some point to counterbalance whatever gain is put in at some other point. Thus a vogad inserted at the transmitting side of one terminal of such a circuit to amplify speech energy from weak talkers must be supplemented by a "reverse vogad" in the receiving side of the circuit. The reverse vogad is simply another vario-losser which is operated upon by the vogad control circuit in such a way that it always has a loss numerically equal to the gain of the vogad. Any vogad gain will be compensated by the reverse-vogad loss, so no greater tendency to sing will be effected by the addition of the combination to the circuit. In like manner half vogads must be used with compensating reverse half vogads.

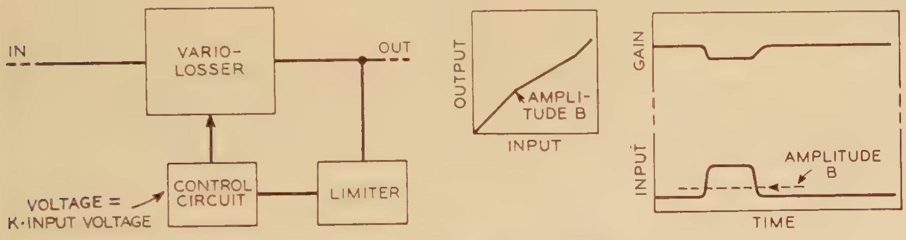

Figure 7. Limited-range compressor

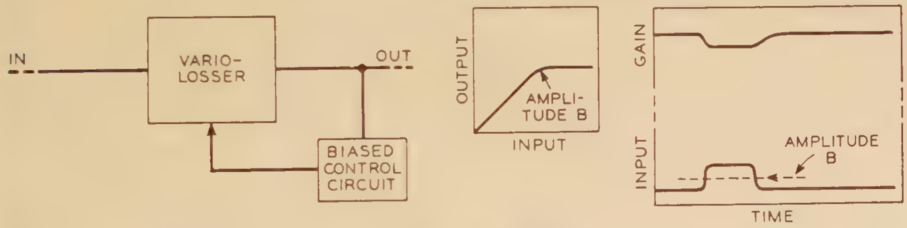

Figure 8. Peak limiter

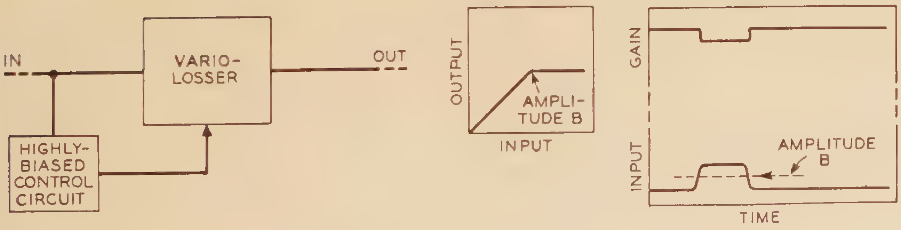

Figure 9. Peak chopper

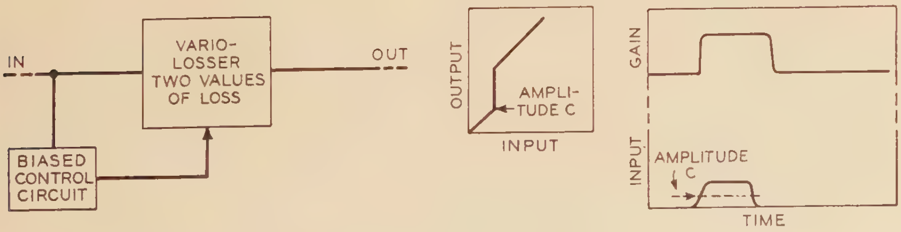

Figure 10. Cross-talk suppressor

Combinations of some of the devices also have interesting characteristics. For example, a combined radio-noise reducer and peak limiter at the receiving end of a circuit would suppress noise and would also reduce the amplitude of excessively high amplitude signals. Likewise, a vogad, compressor, and peak chopper in tandem in the order named could be made to reduce the range of input signals by a very large amount for transmission over a medium having only a small range between noise and maximum permissible signal. In this case it would be practically impossible to recover the original signal range at the receiving terminal of the medium, but the intelligibility of speech over such a system has been shown in the laboratory to be good.

Special compandors for high-quality service may require compression and expansion which varies with frequency. The exact characteristics will depend upon band width, program material, and transmission medium. For transmission media in which the noise reproduced at the receiving end is principally at the higher frequencies an unusual effect is obtained if the usual variety of compandor is used. Low frequencies unaccompanied by high frequencies will cause a gain change in compressor and expandor, thus changing the background of high-frequency noise which is not masked by the low-frequency signal energy. The resulting swishing noise has been given the onomatopoeic name of "hush-hush effect." To avoid this, recourse may be had to split-band compandors in which the compression and expansion is done only at high frequencies or separately for low and high frequencies. The successful application of the latter method is, however, more difficult than it appears from its simple description.

## Distinguishing Characteristics

It is important to distinguish between the half vogad, figure 2 and the compressor, figure 4. As shown in table I the latter operates on syllabic variations and the former on the average volume of the input. Thus the half vogad reduces the range of output volumes to one-half that at the input while the compressor reduces the range of syllabic power at its output to one-half that at the input. In other words, the compressor reduces the ratio of peak to average power on constant-volume speech, while the half vogad simply adjusts for that volume and does not alter the peak ratio. There is, of course, the additional important difference that the half vogad retains its gain setting during silent periods while the compressor, by virtue of having followed the syllabic power, has its maximum gain during silent periods.

Volume limiters, figure 3, may be mistaken for vogads, figure 1, because during speech input above a certain value the two may produce the same output volume. They both employ something like a measurement of average power over periods longer than a syllable to determine their gain settings. The important difference is that a vogad retains its gain setting when speech currents are not present, while a volume limiter approaches its maximum gain during such periods. In terms of the output resulting from a range of input volumes there is another important difference if the volume limiter operates over only part of the input range: the vogad reduces the width of the distribution curve of volumes to a very small value, while the volume limiter moves all the area under the distribution curve above a certain point to the region near that point, which is its limiting volume. This is illustrated in figure 11, in which the calculated modifications of a volume distribution by a vogad and by a volume limiter are shown.

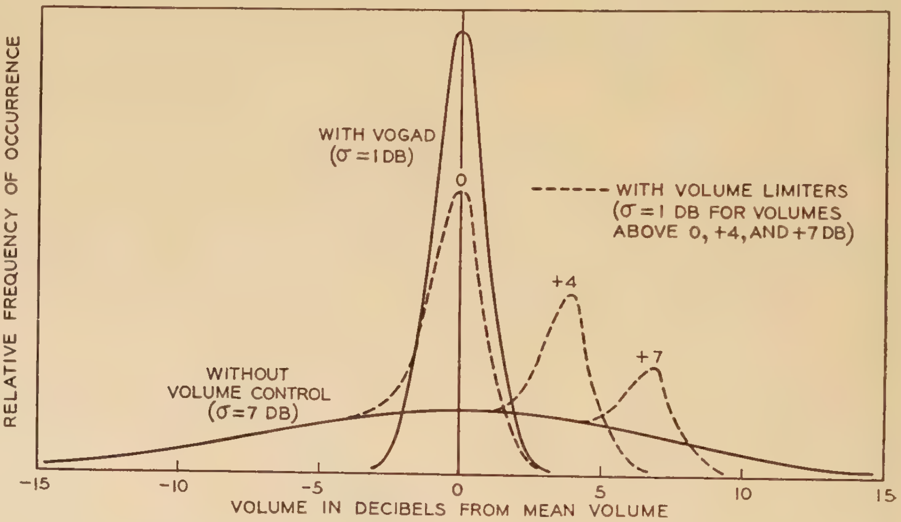

**Figure 11. Modification of volume distribution by use of a vogad or a volume limiter**

In the cases "without volume control" and "with a vogad" the distributions are normal, and the standard deviation, $\sigma$, has its usual statistical significance. With a volume limiter, only volumes above the limiting volume are affected, and these higher volumes are redistributed according to a normal law whose standard deviation is one decibel, as stated in the figure.

It is also important to distinguish between a peak limiter, and a peak chopper, figures 8 and 9. Naturally they resemble one another since they are intended to permit transmission of signals at higher average amplitudes without excessive loading of transmission circuits. However, they are intended for different classes of service and hence are not interchangeable except in some borderline cases. For the highest grade of transmission harmonic production must be negligible and the reduction in amplitude range of signals small and infrequent. Gain changes must be smooth, though rapid enough to compensate for practically any input wave to be expected. These characteristics are found in the peak limiter now being furnished for use on program networks and radio transmitters.[10,11] For services in which it is desirable to maintain the signal energy at a high value to override noise and in which harmonic distortion must be kept low a peak limiter with somewhat smaller time constants may be used. A high-ratio limited-range compressor might be suitable in this instance. This device would lower its gain a little more quickly on excessive inputs, and it would also reinsert its gain much more quickly; it would affect the naturalness of the sound of the signal more than the slower peak limiter but it would also cause the signal to override noise somewhat better. In a third variety of service the harmonic distortion introduced by a limiter is a secondary matter, the prime consideration being that the peak amplitude of the signal shall not exceed a specified value. This may be because higher-amplitude signals would produce a tremendous increase in distortion or cross talk into other channels or would damage expensive equipment farther along in the circuit. For these cases we may use the fastest possible type of limiter, the peak chopper, which simply cuts off any peak exceeding a certain value.

The cross-talk suppressor, figure 10, is a splendid example of the fine distinction between volume-controlled and voice-operated switching devices. This device has been described, but in the present state of the art its time functions have not been definitely fixed. If the characteristic of loss versus input is made steep enough and the speed of operation fast enough it will sound like a switching circuit and may in fact be replaced by a relay-switched attenuating network. If made somewhat slower and given a smaller slope of loss versus input it approaches the limited-range expandor or noise reducer.

## Applications and Expected Advantages

It may be of interest to give some approximate figures on the magnitudes of the advantages to be obtained by the use of some of these devices. It will be understood that the values to be given are simply illustrative, some having been obtained from field service on particular models and some from tests on laboratory equipment under special conditions.

Vogads appear to be most useful in such circuits as transoceanic radio connections, where it is important to operate the terminal switching equipment properly and to transmit over the radio circuit speech energy from loud and weak talkers equally well. It is essential in such cases that noise should not be increased in amplitude during speech pauses, hence the gain retaining feature of the vogad. On such a circuit a vogad will reduce a 45-decibel volume range to about two to four decibels. This is equivalent to expert manual volume control.

Volume limiters are in use at the present time to prevent peaks of speech energy in carrier circuits from "splashing" into telegraph channels.[7] Some five- to ten-decibel limiting is allowed on loudest talkers, which causes little degradation of the speech channels but makes possible the use of telegraph on the same carrier system. There is no widespread use of volume limiters in point-to-point radio service so far, but in cases in which there is no disadvantage in raising noise in silent periods of speech, such as in push-to-talk installations, proper transmitter loading can be obtained with volume limiters fairly cheaply.

One commercial model peak limiter, used as part of a program amplifier[10,11] is capable of introducing a considerable amount of compression without overloading on peaks, but for the preservation of adequate program volume range it is being recommended that only three-decibel peak limiting be allowed. This, of course, reduces the range of intensity of the program, but from the standpoint of the listeners it is equivalent to doubling the transmitted power or obtaining the same signal-to-noise ratio with half the transmitted power.

Limited-range compressors might be used either on land lines to insure full loading or on radio links whose fading is too severe to permit the use of normal compandors. There is no commercial application of either sort at the present time. Peak choppers are, however, used on some high-power radio transmitters which might otherwise be temporarily disabled by high peaks in the signal being transmitted.

The chief usefulness of compandors is on radio links in which the transmission of a compressed signal with subsequent expansion permits operation through higher noise or with lower transmitter power. On a long-wave transatlantic radiotelephone circuit a compandor with 40-decibel range has been shown to allow an increase in noise of some five decibels before reaching the commercial limit.[5] With smaller amounts of noise the noise advantage of the compandor approaches half its range in decibels. This benefit is sometimes applied to a reduction of transmitter power.

Radio noise reducers have been used to advantage in connection with short-wave ship-to-shore and transoceanic radiotelephone service. In the former, routine transmission rating is given on a judgment basis using a merit scale from one to five, five being practically perfect transmission and one so poor that intelligibility is very close to zero. It will then be seen that the observed improvement of one-half to one point in transmission rating due to the noise reducer is of considerable importance. Perhaps more graphic figures are those for transoceanic service, where the reduction of noise in the receiving path not only reduces the noise heard by the listener but also improves the voice-operated switching with the indirect result that at times receiving volume increases of 5 to 15 decibels are realized.[9]

As has been noted, the radio-noise reducer is a special use of an expandor alone. There are also two interesting applications for a compressor alone. The first, which uses a fairly high ratio of compression, has been mentioned as one type of peak-limiting device. The second, using a moderate ratio of compression, is in connection with announcing systems for use in very noisy locations. Its effect is to amplify weak sounds more than strong sounds, which considerably improves the intelligibility through high noise. For quiet locations it is of less value, since the speech sounds lose some of their naturalness in this process.

## Conclusion

In the course of developing various types of the volume-controlled devices which have been described means have been worked out for providing almost any combination of time constants, range of control, and other characteristics which may be required. Some devices for which there were specific commercial applications or useful functional characteristics for experimental work have been constructed, with resulting advantages which have been briefly mentioned. There remain many possible ways to alter the characteristics of signal energy such as speech to which these methods are applicable and which await the special needs of new transmission problems.

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# Testing and Application of Lightning Arresters

FOR some time, information dealing with the testing and application of lightning arresters has been needed. The two memoranda presented herein entitled "General Guide for Utilities on Methods of Testing Lightning Arresters" and "Factors Affecting Application of Arresters" have been prepared by the lightning arrester subcommittee* of the AIEE protective devices committee and provide such information.

## †General Guide for Utilities on Methods of Testing Lightning Arresters

At the meeting of the AIEE lightning arrester subcommittee in New York, January 1937, it was decided that general information regarding methods of testing lightning arresters should be prepared. It was proposed that utilities make tests on new arresters, arresters removed from lines and accumulated in stock in a routine manner, and arresters in service, in order to determine the ability of such arresters to perform satisfactorily in service, as well as to augment, as much as possible, the somewhat limited amount of information now available on the subject of test limits.

The scope of this guide is mainly limited for the present to line-type arresters rated at 15 kv and less, such devices being constructed in accordance with the usual ideas of arresters, that is, with characteristic element having valve action against follow current in series with a gap or set of gaps.

It is desirable to obtain information on test methods, results, and characteristic limits for line and station type arresters rated above 15 kv, in order that this guide may later be expanded to include detailed information on preferred test methods and limiting values for all types and ratings of arresters. In the meantime for arresters rated above 15 kv, it will usually be preferable to obtain the assistance of the manufacturers in connection with the test methods to use and the interpretation of test results.

It is expected that, after more experience is obtained, the outline of test methods and the data on test limits will be expanded and improved as information becomes available.

### Impulse Tests

Impulse tests are used to determine the surge protective characteristics of arresters, while 60-cycle tests indicate the internal condition of arresters and the relation of breakdown voltage to rated voltage. Impulse tests on new and used arresters should follow, in general, the test method prescribed in AIEE Standard No. 28. To determine the condition of the arrester when new or when removed from service, an impulse should be applied to the arrester and breakdown and impedance drop voltages obtained by means of a cathode-ray oscillogram. These values should be compared with corresponding values for new arresters as given for 3- to 15-kv arresters in the paper "Distribution Lightning Arrester Performance Data," ELECTRICAL ENGINEERING, May 1937, page 576, or as furnished by the arrester manufacturer for all ratings.

To determine the ability of an arrester to operate satisfactorily in service without change in its characteristics, the AIEE standard operating-duty test (AIEE 28-234) should be applied. As this test requires that the arrester be subjected to 60-cycle voltage during the application of impulses, it may be feasible to make such tests while the arrester is connected to the lines.

### 60-Cycle Tests

#### TEST CIRCUIT

Three suitable circuits for conducting tests at 60 cycles on arresters are illustrated in the attached figure 1. These circuits are essentially similar, comprising means for applying a variable voltage up to the breakdown voltage of the arrester, and meters for indicating the voltage applied to, and leakage current through, the arrester. An essential part of the test set is a current-limiting resistor $R_1$, located in either the low-voltage or high-voltage side of the test circuit, of such value as to limit the current during breakdown to a value which will not damage the arrester. Limiting values of from 3 to 15 milliamperes through the arrester

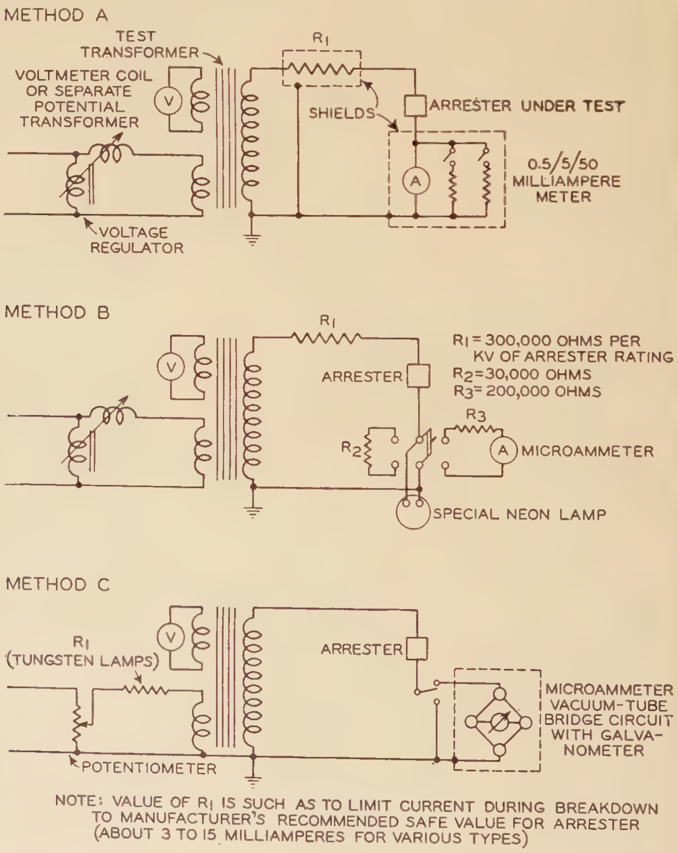
METHOD A
TEST TRANSFORMER
VOLTMETER COIL OR SEPARATE POTENTIAL TRANSFORMER
V
R1
SHIELDS
ARRESTER UNDER TEST
A
0.5/5/50 MILLIAMPERE METER
VOLTAGE REGULATOR
METHOD B
V
R1
R1 = 300,000 OHMS PER KV OF ARRESTER RATING
R2=30,000 OHMS
R3= 200,000 OHMS
ARRESTER
R2
R3
A
MICROAMMETER
SPECIAL NEON LAMP
METHOD C
R1
(TUNGSTEN LAMPS)
V
ARRESTER
MICROAMMETER VACUUM-TUBE BRIDGE CIRCUIT WITH GALVANOMETER
POTENTIOMETER
NOTE: VALUE OF R1 IS SUCH AS TO LIMIT CURRENT DURING BREAKDOWN TO MANUFACTURER'S RECOMMENDED SAFE VALUE FOR ARRESTER (ABOUT 3 TO 15 MILLIAMPERES FOR VARIOUS TYPES)

**Figure 1. Circuits for 60-cycle tests of lightning arresters**

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† Prepared under the sponsorship of Herman Halperin.

* Personnel of the AIEE lightning arresting subcommittee: J. R. North, *chairman;* H. W. Collins, R. H. Earle, I. W. Gross, Herman Halperin, C. F. Harding, K. B. McEachron, J. R. McFarlin, A. M. Opsahl, A. H. Schirmer, H. K. Sels, L. G. Smith, A. H. Sweetnam, and J. J. Torok.

have been used or suggested. For the test circuit shown as method *B*, the limiting leakage current during breakdown may be as low as three milliamperes. For testing arresters with different voltage ratings, the resistance should be variable or provision made for the insertion of resistors of proper values.

For methods *A* and *B*, the drop of voltage in the resistor $R_1$ in the circuit directly including the arrester should be taken into account in determining the voltage across the arrester.

Control of the test voltage may be accomplished by either a regulator or a potentiometer. If a voltmeter coil in the test transformer or a separate potential transformer is used to measure the applied voltage, the voltmeter should preferably be calibrated against the crest voltage applied to the arrester, but should give readings of root-mean-square values of the equivalent sine wave.

In one of the circuits shown, a neon tube is used to detect breakdown; the others use the voltmeter or microammeter indication. For the latter case the meter should be able to withstand the current during breakdown without being damaged. This meter, to accomplish its primary purpose of measuring leakage current through the arrester, should have a range of from about 10 microamperes to 3 or 5 or 15 milliamperes.

Care should be taken that stray electrostatic fields or capacitive currents do not affect the leakage current measurements. This may be prevented by suitable shielding, as indicated in two of the sketches, or by physically isolating the microammeter and arrester from each other and from the remaining testing equipment. If desired, the arrester under test may itself be shielded by placing it in a grounded metal box.

## TEST PROCEDURE

1. In 60-cycle tests, there must be no other voltage on the arrester than the test voltage. This means that, for arresters installed on the system, the arrester must be disconnected from the lines before being tested for breakdown voltage.

Sixty-cycle leakage current measurements at operating voltage, however, can possibly be made on the arrester as installed. Due to the necessity for careful shielding against stray fields, such testing of arresters in service should be considered as developmental work and investigated by each utility planning tests on installed equipment.

2. With the microammeter in the test circuit, the leakage current through the arrester is usually measured at the rated voltage of the arrester.

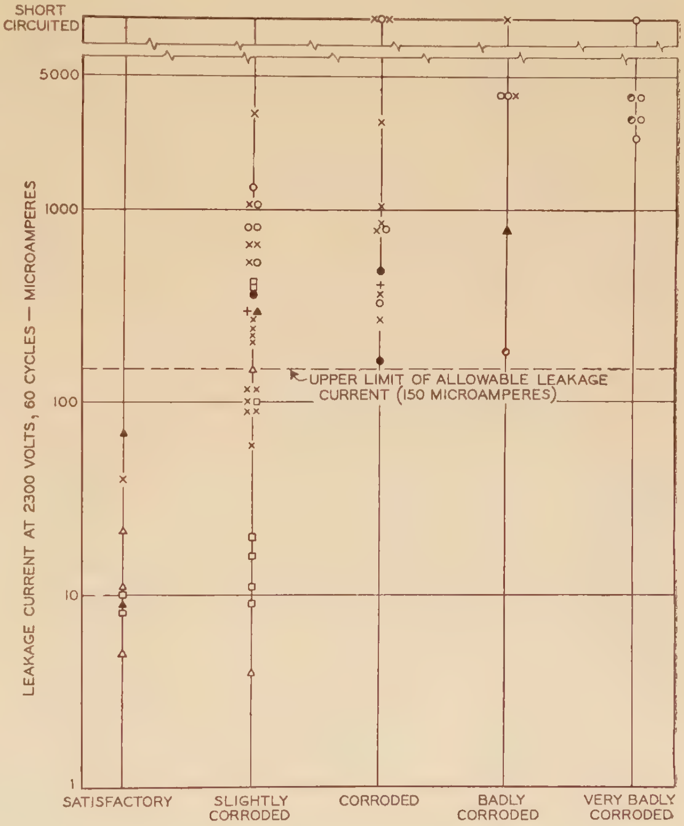
3. The microammeter is either cut out of the circuit or shunted by resistance. The test voltage is then gradually increased to the breakdown point of the arrester. The breakdown voltage and breakdown characteristic (whether sharp or gradual) are indicated by the neon lamp, if used, or by the voltmeter or shunted microammeter.

## SUGGESTED TEST LIMITS

Insufficient data are as yet available to indicate sharply the test limits differentiating between satisfactory and unsatisfactory arresters removed from service. For satisfactory three-kv line type arresters, one utility has found from its experience and examinations of used arresters that the upper limit of leakage current should be about 150 microamperes at the normal operating voltage, that is, 2,300 volts. For other voltage ratings, this value might be subject to modification because of varying ratios of test (or operating) voltage rating. Further work seems necessary to establish proper values for all voltages.

**Figure 2. Comparison of leakage currents of used three-kilovolt arresters with condition of gap found on examination**

Each symbol represents a different type of arrester



Arresters of modern manufacture generally have 60-cycle breakdown values between 1.5 and 3.0 times the rated arrester voltage. These ratios result in the limits shown in table I.

**Table I**

| Rated Voltage (Kv) | Usual Limits of 60-Cycle Breakdown Voltages (Kv-RMS) | |
|---|---|---|
| | Minimum | Maximum |
| 3 | 4.5 | 9 |
| 6 | 9 | 18 |
| 9 | 13.5 | 27 |
| 12 | 18 | 36 |
| 15 | 22.5 | 45 |

Due to the differences in designs, it will probably be desirable to determine the ratios for each manufacture, type, and vintage of arrester.

It has been found occasionally for modern arresters, especially for some removed from service, that the 60-cycle breakdown voltage for satisfactory arresters has been outside the limits given in the above table. In such cases the variation is usually on the low side; that is, the 60-cycle breakdown was found to be 1.2 to 1.4 times the rated voltage.

For arresters of older designs, the limits of 60-cycle breakdown voltages have been found for apparently satisfactory arresters to vary between 1.1 and 3.5 times the rated voltage. Usually, however, the test limits have been between 1.5 and 3 times the rated voltage. The outstanding exception, however, has been reported for some old three-kv arresters of two types where the breakdown voltage for apparently satisfactory arresters has been found to be as high as about five times the rated voltage.

In order to set up adequate test limits, both for leakage current and for breakdown value, which may be used to differentiate between satisfactory and defective arresters, it is suggested that each utility, in the preliminary stages of its 60-cycle arrester testing, conduct an investigation on the various classes of arresters removed from service. The recommended procedure is to test each arrester, then dissect particularly those having suspicious test values, and inspect for internal defects. The attached figure 2 indicates the procedure followed by one utility, for example, in determining the proper maximum limit of leakage current for three-kv line-type arresters. The values given above for breakdown voltage limits should also be checked in a similar way and modified, if necessary.

As a guide in analyzing the data obtained in examinations of dissected arresters, the various test indications are listed below with the conditions which generally cause them:

*High Breakdown Voltage*

Fundamental arrester design.
Gap electrodes burned away in service.
Loss of characteristic element material.
Destruction of internal parts.

*Low Breakdown Voltage*

Gap electrodes welded or short-circuited in service.
Gap electrodes short-circuited by corrosion products.

*Unsatisfactory Discharge Action on Breakdown (gradual breakdown, or high resistance after breakdown)*

Fundamental arrester design or assembly.
Change in characteristic element.
Corrosion.

*Excessive Leakage Current*

Corrosion of gap assemblies (principal cause).
Gap electrodes welded or short-circuited.

## Radio-Interference Tests

If frequent cases of radio interference are caused by lightning arresters, then in addition to the 60-cycle tests described above, it is suggested that radio-interference tests be made on arresters with rated voltage applied. Tests should be made in accordance with Edison Electric Institute Publication No. C-9 "Methods of Measuring Radio Noise."

## Correlation of Surge and 60-Cycle Data

In order to determine whether any correlation exists between surge data, 60-cycle data, and arrester condition, it is suggested that, where facilities are available, arresters be tested by both methods. The greatest amount of information is to be obtained by testing arresters which are to be dissected for examination.

## Co-ordination of Data

Data covering the testing experience of each utility should be forwarded for co-ordination to the subject committee sponsor, Herman Halperin, Commonwealth Edison Company, Chicago, Ill. Such data should include the following: testing circuits and methods, limits of and detailed data used in arriving at limits of acceptable test characteristics, correlation of surge and 60-cycle data, and general test results and conclusions. It is also desirable to follow and report on the protective performance obtained in service with used arresters which were tested before reuse.

# *Factors Affecting Application of Arresters

A great deal has been published in technical papers and manufacturers' bulletins about the application of lightning arresters. There are a number of factors involved, many of which have been discussed in other papers. Some of these more important factors are:

(*a*). Characteristics of equipment to be protected.

(*b*). Performance characteristics of arresters.

(*c*). Margin between arrester performance and equipment characteristics.

(*d*). Deterioration of arresters and equipment.

(*e*). When to use line-type or station-type arresters.

(*f*). Influence of circuit feet between arrester and equipment to be protected.

(*g*). Influence of multiple arresters.

This memorandum deals only with the selection of arrester ratings and methods of connection for distribution transformer protection. Certain factors such as when to use line-type versus station-type arresters, influence of distance between arresters and protected equipment, and influence of multiple arresters, are largely matters of individual application.

## Selection of Arrester Rating

The principal factors that should be considered in the selection of the rating of a surge protective device, such as a lightning arrester or a gap, are:

(*a*). The maximum dynamic voltage which may occur between sound phase and ground under any fault conditions. The device should withstand this voltage without failure.

(*b*). The efficacy of the protective device in maintaining a low protected level and at the same time meeting satisfactorily the system operating requirements. The impulse volt-time characteristics of the device must be below that of the equipment to be protected.

(*c*). The surge current which must be satisfactorily discharged. The thermal ability of the device must be adequate for the currents expected, and the voltage drop across the arrester during discharge must be sufficiently low to provide satisfactory protection.

The voltage rating of an arrester represents the maximum dynamic voltage which the arrester can withstand continuously and which it can interrupt after functioning. The arrester rating must be not less than the maximum dynamic voltage which may occur between the arrester terminals during disturbances, allowing for the power system neutral being isolated, or grounded, as the case may be, and considering the actual maximum operating voltage. Allowance must also be made for the voltage recovery rate and any overvoltage conditions which may exist due to the overspeeding of hydroelectric generators, etc. The protection afforded by a lightning arrester is approximately proportional to its voltage rating and, therefore, it is important to use an arrester of as low a voltage rating as possible.

The normal "full voltage" rated arrester is designed to operate on an ungrounded or isolated neutral system where the voltage existing between line and ground may at times equal the normal line-to-line voltage. The arrester rating selected is generally five per cent or more above the maximum operating line-to-line voltage. Under favorable conditions where the system neutral is effectively grounded, better protection can be obtained by the use of an arrester having a reduced voltage rating, provided the upper limit of dynamic voltage of the arrester is not exceeded under any operating or fault condition. In the past, "grounded neutral" arresters have had voltage ratings approximately 80 per cent of the "full rated" arresters. This gave a wide margin above the normal system line-to-neutral voltage but a margin which is required to allow for fault voltages, etc.

For the purpose of determining the allowable arrester voltage rating, the maximum dynamic voltage which may occur during fault conditions between the sound phases and ground may be calculated by the method of symmetrical components ("Symmetrical Components" by Wagner and Evans, McGraw-Hill Book Company). Under certain conditions, a two line-to-ground fault may be slightly more severe than a single line-to-ground fault.

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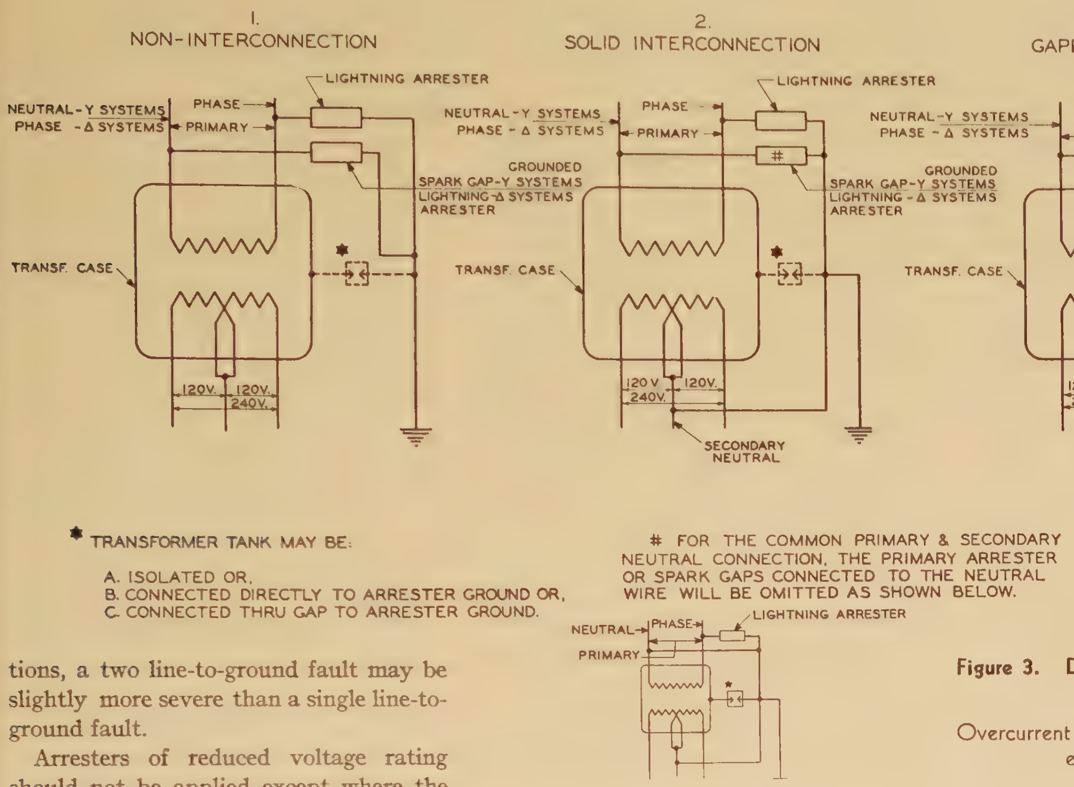
*Prepared under the sponsorship of J. R. North.



* TRANSFORMER TANK MAY BE:

A. ISOLATED OR,
B. CONNECTED DIRECTLY TO ARRESTER GROUND OR,
C. CONNECTED THRU GAP TO ARRESTER GROUND.

# FOR THE COMMON PRIMARY & SECONDARY NEUTRAL CONNECTION, THE PRIMARY ARRESTER OR SPARK GAPS CONNECTED TO THE NEUTRAL WIRE WILL BE OMITTED AS SHOWN BELOW.

**Figure 3. Distribution-transformer-protective schemes**

Overcurrent protection may be internal or external to transformer

Arresters of reduced voltage rating should not be applied except where the neutral is "effectively grounded" and the following conditions are met:

(*a*). The neutral of that portion of the system must be grounded at all times and under all operating conditions.

(*b*). The ratio of zero sequence reactance (including neutral reactance) to positive sequence reactance or negative sequence reactance $X_0/X_1$ or $X_0/X_2$ must be equal to two or less under the most severe fault conditions. Due consideration must be given to the circuit impedance as affected by sequential operation of circuit breakers.

It is recommended that the arrester voltage rating be at least ten per cent above the calculated maximum sound phase voltage to ground.

As a rough rule of thumb, in many cases, it will be found that:

1. If $X_0/X_1 = 2$ or less, an 80 per cent arrester may be used.

2. If $X_0/X_1 = 1$ or less, a 70 per cent arrester may be used.

These latter percentages should be applied to the *maximum* root-mean-square line-to-line voltage, which may exist under the most unfavorable operating condition, in determining the allowable arrester rating.

## Connections of Lightning Protective Equipment on Distribution Circuits

The problem of protecting transformers against lightning is essentially a question of definitely limiting the surge voltage stress on the transformer insulation to values that it can withstand by the proper use of arresters or gaps, while coincidently providing a suitable path to ground for the surge.

Conventional practice provides a more or less suitable ground path for the surge by the use of lightning arresters or gaps connected between line and ground, but does not provide for the coincident necessity of definitely limiting the voltages that can appear across the transformer insulation during the surge discharge, except in the limiting case of negligible arrester ground resistance. As a consequence, primary to secondary flashovers frequently occur, resulting at least in blown transformer fuses with attendant service interruptions, if not in equipment failure, etc.

By providing suitable "interconnection" between arresters, secondaries, and tanks, the surge potential across the transformer insulation may be limited to the voltage drop across the terminals of the protective devices themselves which, in the event the latter are suitably chosen, will eliminate the great majority of the transformer service outages otherwise experienced. The benefits to be derived from interconnection are not limited to single-phase installations, but may be extended to include the customary polyphase installations as well.

It is not essential to permanently ground the transformer tank, from the standpoint of protecting the transformer itself. While interconnection eliminates the arrester ground resistance as a factor in the protection of the transformer itself, the necessity of providing a low resistance path to ground in order to finally dispose of the surge is just as important as ever.

There are various ways of connecting arresters and gaps between distribution transformer leads, the tank and ground. Also, different nomenclature has been used to describe these various connections. In order to avoid lengthy descriptions or drawings every time a certain connection scheme is mentioned, it is very desirable to adopt a uniform system of titles.

Figure 3 shows the more common connections used for protecting distribution transformers. The numerous schemes of connections have been grouped into three general classes and each class subdivided to cover the more detailed connections. This method of identification makes it possible to describe the scheme of connections used by simply stating whether a "non," "solid," or "gapped" interconnection is used and whether the transformer tank is isolated, grounded, or connected to ground through a gap.

# An Application of Deceleration Test Methods to the Determination of Induction-Motor Performance

By RAYMOND W. AGER
ASSOCIATE AIEE

RETARDATION tests have been used by industry for a long time. They have found their main applications in the determination of certain machine losses, usually friction and windage and core loss. The machines to which these methods have been applied have ordinarily had large mass and low rotational losses with the result that a considerable time would elapse between the time the power was shut off and the time the machine would come to rest. By proper selection of equipment and analysis the same methods may be applied to much smaller machines having relatively short stopping periods. In the present instance the methods have been applied to two double squirrel-cage induction motors, one a $7^1/_2$-horsepower 6-pole machine, and the other a 5-horsepower 4-pole machine. In each case the inertia was increased to about twice that of the motor alone by the use of a small flywheel. A similar analysis has been applied to acceleration tests on these two motors in which the motors were started at reduced voltage. By combining the acceleration tests with the decleration tests the speed-torque curves of the motors have been obtained. It is hoped that the discussion of the difficulties and the results of these tests will help to indicate the value and limitations of the methods as applied to similar determinations in this and other fields.

## Quantities Involved and Their Measurement

There are five quantities involved in deceleration tests. These are inertia, time, position, velocity, and acceleration.

Inertia may be determined by calculation or test with the required accuracy. Its determination is not considered a part of this paper.

Time may be measured with extremely high accuracy. In the measurement of very short periods of time, however, a high-grade stop watch is almost useless since the registration does not go below one-fifth second. The synchronous clock will give indications to as fine a subdivision as desired but this indication can be relied upon only if the driving source has constant frequency. Some power systems are operated with a frequency control of sufficient accuracy for these measurements. One should not assume that the power frequency is constant just because electric clocks keep good time. Satisfactory time service for general use does not necessarily indicate that momentary or continuous fluctuations in frequency are absent. If the power-system frequency is not constant some other driving source for the clock should be used.

Position also can be measured with very high accuracy. Using a relatively small dial attached to the motor shaft, the rotor position can be estimated to 0.01 revolution. By increasing the dial size the position can be determined with greater accuracy.

Velocity is a derived quantity and cannot be measured directly with the accuracy with which one can measure fundamental quantities. Tachometers, whether electrical or mechanical, are subject to errors several times those which may exist in the measurement of time or position. The velocity may be determined more accurately from a properly taken distance-time curve than by direct measurement using tachometers. Another difficulty encountered in the use of tachometers is the load which the instrument places upon the machine being tested. If the machine being tested is small, the instrument may represent a burden which will mask the effects it is desired to measure.

Acceleration is a derived quantity of the second order. Satisfactory instruments for the measurement of accelerations as small as those found in deceleration tests are not available. The determination of acceleration must therefore be based upon calculations involving the velocity, which for best results must in turn be based upon the distance-time curve.

Since so much depends upon the distance-time curve, very high accuracy is required in its determination. It has been found that it is necessary to determine the time and the position with an error not exceeding about 0.002 times the difference between successive readings if truly good results are desired. In other words, if readings are taken ten seconds apart the time of reading must be known to about 0.02 second. If the readings are taken one second apart the individual readings must be accurate to about 0.002 seconds. Similar limits hold for the measurements of distance or position. The readings must also be known to be simultaneous within the same limits of time as indicated above. Photographic recording has been used in this work to obtain the simultaneous readings. This method of recording has other advantages as well in that a permanent record is obtained from which readings may be checked at any time, the rate of taking readings is under better control, and it is possible to photograph other dials on these same films giving simultaneous readings of other related quantities. This has been done in one acceleration test in which a voltmeter, an ammeter, and a polyphase wattmeter were photographed along with the time and displacement dials and their readings used to get the electrical characteristics of the motor.

## Apparatus

The timing device was a synchronous clock, made for checking relay settings, etc. It was of the continuously rotating type and did not have the intermittent motion of the cycle counter. The clock had two hands, one of which made one revolution per second, and the other made one revolution in ten seconds, when supplied with 110-volt 60-cycle alternating current. The dial was calibrated with 100 divisions and time could be estimated to 0.001 second.

The position indicator was a watthour meter register which had the units dial directly coupled to the motor shaft. The coupling was by means of a tightly wound piano-wire flexible shaft slipped over a pin set in the center of the motor shaft on one end, and over the shaft of the units dial of the register on the other end. With the two shafts in line the hand appeared to follow the shaft movement accurately.

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The rotor position was estimated to 0.01 revolution.

The photographic equipment consisted of a candid camera clamped into position and accurately focused on the dials. The camera had a focal-plane shutter which was wound and tripped by hand. The camera had a maximum capacity of about 40 pictures at one loading. This number of pictures was adequate for most tests, although a slightly larger number could have been used to advantage at times. The marked shutter speeds ranged up to $^1/_{500}$ second but the actual exposure was found to be about twice this. Shorter times of exposure would have resulted in better images of the faster moving pointers, but the values obtained by estimating the position of the centers of the blurs caused by the moving pointers seem to have all the accuracy required. A distance of 30 inches between the camera and the dials was found to be satisfactory using the two-inch-focal-length lens.

The dials were illuminated by "photoflood" lamps. The lens was stopped down so that the resulting negatives would be much thinner than would be used for the more normal photographic work since it was found to be easier to read these thinner negatives. The readings were taken from the films using a pocket magnifying glass of about six power.

Standard portable-type voltmeters, ammeters, and wattmeters were used in the acceleration test in order to get the complete electrical characteristics. Figure 1 shows these instruments, the synchronous clock, and the position-indicator dial as they were grouped around the motor in the acceleration test.

## Calculations

Because of the high accuracy of the data taken from the films, the velocities may be calculated from the differences between successive readings. That is, if the difference in distance (revolutions) as read from two successive films is divided by the difference in time as read from the same films, the average velocity during the interval is obtained. This calculation is indicated in table I, which lists the readings for the acceleration test of the $7^1/_2$-horsepower motor. The first and second columns contain the distance and time readings as they were taken from the films. The third and fourth columns show the differences referred to above, while the fifth column lists the quotient of these differences or the average velocities during the intervals. If each interval is of short enough duration so that the change in velocity is small during that interval, this average velocity may be considered as the true velocity at the time corresponding to the middle of the interval. How close this will be to the truth will depend upon the curve to which the calculations are applied. No approximations are involved if the velocity is a straight-line function of the time. The times corresponding to the velocities listed in the fifth column of table I are shown in the sixth column. However, if one is interested in the velocity-distance curve, the average velocity found above may be considered as the true value at the mid-distance of the interval. The accuracy of this approximation again depends upon the shape of the curve. In this case no approximation is involved if the velocity is a straight-line function of the distance. It is to be noted that the mid-distance and the mid-time points do not fall on the true curve of time and distance, but on straight lines joining successive points on the original curve.

It might seem that the velocity could be obtained by graphical means from the distance-time curve. It was not found to be feasible to do it this way, since the plotting of the curve could hardly be done with an accuracy comparable with that of the original data, unless the plot were made to an enormous scale. The process of calculating differences as outlined above results in accurate velocity data with a minimum amount of manipulation.

Now if a sufficient number of readings of distance and time have been obtained in the original data, a velocity-time curve or a velocity-distance curve may be derived having high enough accuracy for use in determining the acceleration. The slope of the velocity-time curve is equal to the acceleration. If one wishes to use the velocity-distance curve, he may find the acceleration by multiplying the velocity by the slope of this curve. This relationship may be shown as follows:

Since

$$v = ds/dt$$

and

$$a = dv/dt$$

$$\frac{a}{v} = \frac{dv}{dt} \times \frac{dt}{ds} = \frac{dv}{ds}$$

or

$$a = v\frac{dv}{ds}$$

It is to be noted that in either case the slope of a curve must be found. The accuracy with which one can determine the slope of an experimental curve depends upon the shape of the curve and the accuracy with which the location of the curve is known. The supposedly slight variations which would be expected in the judgment of curve location may produce relatively large changes in the slope of adjacent parts of the curve. The easiest and most accurate curve to draw, and the easiest one from which to determine slopes is that curve which approximates a straight line. Also, as inferred in the preceding paragraphs, this would be the one which would have the better approxi-

### Table I

| Revolutions | Time | Revolution Difference | Time Difference | Velocity | Time | Velocity Difference | Time Difference | Acceleration | Velocity |
|---|---|---|---|---|---|---|---|---|---|
| 143.24 | 0.002 | 0.37 | 1.516 | 0.24 | 0.760 | 1.15 | 1.787 | 0.644 | 0.84 |
| 143.61 | 1.518 | 2.85 | 2.058 | 1.39 | 2.547 | 1.14 | 1.789 | 0.638 | 1.96 |
| 146.46 | 3.576 | 3.84 | 1.519 | 2.53 | 4.336 | 0.89 | 1.477 | 0.602 | 2.97 |
| 150.30 | 5.095 | 4.92 | 1.436 | 3.42 | 5.813 | 0.87 | 1.470 | 0.592 | 3.85 |
| 155.22 | 6.531 | 6.45 | 1.504 | 4.29 | 7.283 | 0.82 | 1.513 | 0.542 | 4.70 |
| 161.67 | 8.035 | 7.79 | 1.522 | 5.11 | 8.796 | 0.86 | 1.538 | 0.560 | 5.54 |
| 169.46 | 9.557 | 9.28 | 1.554 | 5.97 | 10.334 | 0.87 | 1.637 | 0.531 | 6.41 |
| 178.74 | 11.111 | 11.75 | 1.719 | 6.84 | 11.971 | 0.91 | 1.677 | 0.542 | 7.30 |
| 190.49 | 12.830 | 12.69 | 1.636 | 7.75 | 13.648 | 0.83 | 1.665 | 0.498 | 8.17 |
| 203.18 | 14.466 | 14.54 | 1.694 | 8.58 | 15.313 | 0.83 | 1.689 | 0.491 | 9.00 |
| 217.72 | 16.160 | 15.85 | 1.685 | 9.41 | 17.002 | 0.84 | 1.708 | 0.492 | 9.83 |
| 233.57 | 17.845 | 17.74 | 1.730 | 10.25 | 18.710 | 0.82 | 1.723 | 0.476 | 10.66 |
| 251.31 | 19.575 | 18.99 | 1.715 | 11.07 | 20.433 | 0.79 | 1.697 | 0.466 | 11.47 |
| 270.30 | 21.290 | 19.90 | 1.679 | 11.86 | 22.130 | 0.72 | 1.631 | 0.441 | 12.22 |
| 290.20 | 22.969 | 19.91 | 1.583 | 12.58 | 23.761 | 0.71 | 1.650 | 0.430 | 12.94 |
| 310.11 | 24.552 | 22.83 | 1.718 | 13.29 | 25.411 | 0.77 | 1.784 | 0.431 | 13.67 |
| 332.94 | 26.270 | 26.01 | 1.850 | 14.06 | 27.195 | 0.64 | 1.692 | 0.378 | 14.38 |
| 358.95 | 28.120 | 22.55 | 1.534 | 14.70 | 28.887 | 0.60 | 1.575 | 0.381 | 15.00 |
| 381.50 | 29.654 | 24.71 | 1.615 | 15.30 | 30.462 | 0.65 | 1.595 | 0.407 | 15.62 |
| 406.21 | 31.269 | 25.14 | 1.576 | 15.95 | 32.057 | 0.57 | 1.658 | 0.344 | 16.23 |
| 431.35 | 32.845 | 28.77 | 1.741 | 16.52 | 33.715 | 0.60 | 1.741 | 0.344 | 16.82 |
| 460.12 | 34.586 | 29.78 | 1.740 | 17.12 | 35.456 | 0.56 | 1.683 | 0.333 | 17.40 |
| 489.90 | 36.326 | 28.73 | 1.626 | 17.68 | 37.139 | 0.44 | 1.619 | 0.272 | 17.90 |
| 518.63 | 37.952 | 29.23 | 1.613 | 18.12 | 38.758 | 0.43 | 1.652 | 0.260 | 18.34 |
| 547.86 | 39.565 | 31.35 | 1.690 | 18.55 | 40.410 | 0.41 | 1.705 | 0.240 | 18.75 |
| 579.21 | 41.255 | 32.62 | 1.721 | 18.96 | 42.115 | 0.16 | 1.752 | 0.091 | 19.04 |
| 611.83 | 42.976 | 34.06 | 1.782 | 19.12 | 43.867 | | | | |
| 645.89 | 44.758 | | | | | | | | |

mations. One should therefore use the curve which more closely approximates a straight line.

These graphical methods for determining the acceleration from the velocity curves were used in the preparation of this article. As an extension of the method of taking differences to the determination of acceleration the last four columns of table I have been calculated, and further indicate the surprising accuracy of the data. The figures shown in the seventh and eighth columns are the velocity and time differences calculated from the values shown in the fifth and sixth columns. The quotients obtained by dividing these velocity differences by the corresponding time differences are the accelerations and are listed in the ninth column. The last column contains the velocities corresponding to the accelerations.

## Accuracy of the Data

Although the foregoing shows very well the high accuracy which may be obtained, further improvement is possible so that some consideration of the sources of errors may be of value.

First consider the ability of the dials to follow time and position. The time dial should record time with the same accuracy as that with which the frequency is held constant at rated value. The tests which are reported were made on two large power systems. In one case the frequency fluctuations were of no consequence and the results are entirely reliable on this point. In the other case the frequency fluctuations were such that the results are somewhat in question. In this case the results of duplicate tests were similar but not identical. The distance or position dial should follow the motion of the rotor if the coupling is rigid. At first the coupling used was thought to be satisfactory as long as the shafts coupled by it were in line and the coupling was kept from vibrating. It is now believed that the greatest inaccuracies in this work originate here.

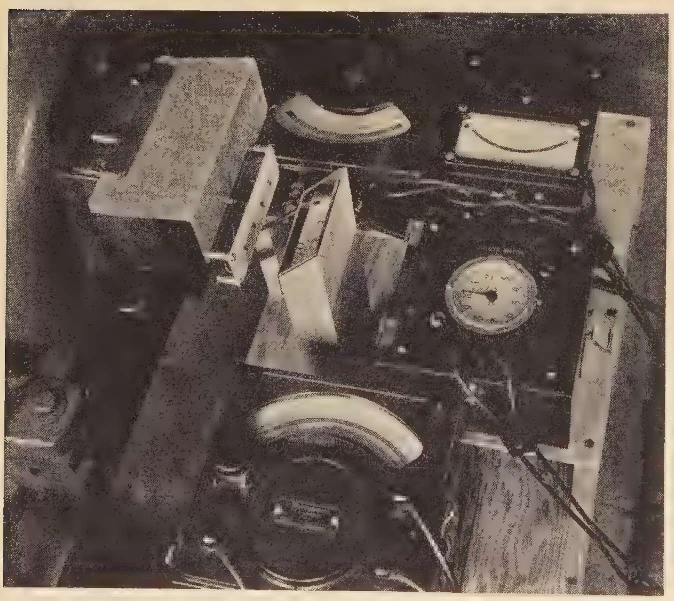

Figure 1. General view of the instruments grouped for photographing in the acceleration test

Since the camera had a focal-plane shutter the time of recording was not simultaneous over the entire picture. The progression of the exposure across the film should be the same in each picture and so should cause no errors due to the placing of the dials. However, an error will exist due to this sweeping action, since different portions of a single dial are photographed at slightly different times. Some irregularities in the curves have been traced to this source.

## Procedure

From the above the general procedure should be obvious. Some of the details of procedure which must be watched will bear discussion. Bearing friction is a determining factor in these tests. Its value will vary with the bearing temperature, the load on the bearings, the axial position of the rotor, and the thickness of the oil film, as well as with the motor speed, the kind of oil used, and the general design.

Bearing temperature is very important. Changes in bearing temperature may affect the results to such an extent that any conclusions drawn from the tests may be entirely erroneous. This statement applies to ball-bearing machines as well as to those equipped with sleeve bearings. On successive tests on a new ball-bearing machine the bearing friction varied in the ratio of four to three although the time of running before the second test was only slightly greater than that before the first. The preferred procedure would be to run the motors to constant bearing temperatures before taking readings.

The addition of a flywheel to a motor may change the bearing friction and also the windage. In these tests all runs were made with identical flywheel loading and hence the effects of the flywheel should cancel out of the final result.

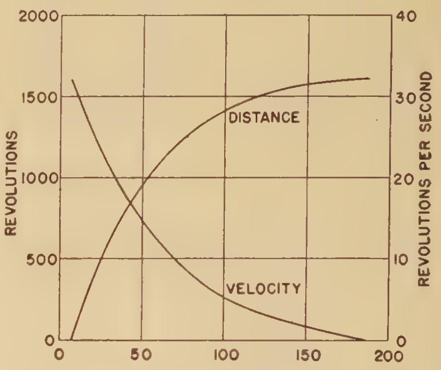

Figure 2. Distance-time and velocity-time curves for the deceleration test on the $7^1/_2$-horsepower 6-pole motor

The axial position of the rotor may affect the bearing friction, or, by changing fan clearances, change the windage loss. This difficulty is not experienced in ball-bearing machines where end-play is restricted, but in sleeve-bearing machines there may be a tendency for the rotor to shift from its normal position during the test unless the shaft is carefully leveled and perhaps lightly restrained.

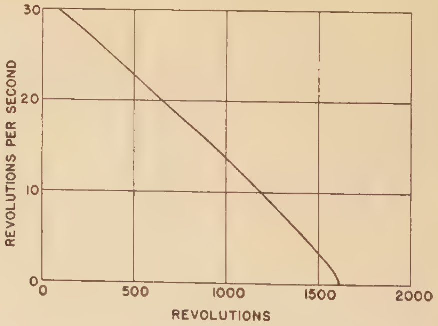

Figure 3. Velocity-distance curve from the test of figure 2

In deceleration tests the oil film should be properly maintained by the motion of the rotor. In acceleration tests, starting from rest, it may take several revolutions before the oil film is built up to its proper value. It is therefore important to start acceleration tests after a period of running without allowing time for the rotor to settle and squeeze out the oil film.

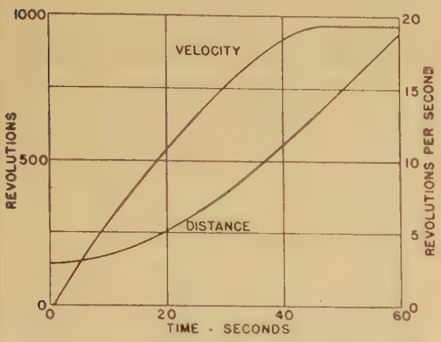

**Figure 4. Distance-time and velocity-time curves from the acceleration test on the $7^1/_2$-horsepower 6-pole motor**

In trying to avoid the change in the oil film in the acceleration tests two methods were employed. The first was to run the machine and then allow it to coast to rest. The test was started within about one second of the time the motor stopped. The second method was to run the machine in the reverse direction and then to plug it on the line. Recording was started as the motor reversed. In analyzing the results of the tests made using the first method it was found that there was an apparent delay in the starting of the motor. In figure 4 this delay is indicated. In this test the power was applied at the time $t$ = 0.002. This apparent delay is believed to be due to the inductance of the rotor circuit, which does not permit the field to build up instantaneously, and to transients which may exist at the closing of the line switch. The net result is that full torque is not available until some time after the closing of the switch and, therefore, the speed increases more slowly than it should at first. By plugging the motor on the line the time required for the building up of the field and the decay of the transients was provided before recording was started.

On deceleration tests the motor field tends to collapse on the removal of the applied voltage but is held trapped by the short-circuited rotor winding. Therefore, during the first few seconds the losses of the machine which must be supplied by the rotational energy include a stator core loss. Only after the rotor resistance has dissipated the energy of the field does this loss become zero and the friction and windage losses remain alone. A simple means of avoiding this core-loss error is to supply the motor with a higher frequency, running it at overspeeds so that the field will have become negligible by the time the speed has decreased to normal.

Since the camera used had a limited number of exposures, it was necessary to space these properly throughout the time of the test. In the deceleration tests the velocity-distance curves approximated straight lines and so were used in preference to the velocity-time curves. Since distance was used for the abscissa in these curves, a fairly uniform spacing of points on the curves was obtained by taking readings at approximately equal intervals of distance. In the acceleration tests, however, the velocity-time curves were more nearly straight lines and were therefore used in determining acceleration. For these tests proper spacing of points was obtained by taking readings at approximately equal intervals of time.

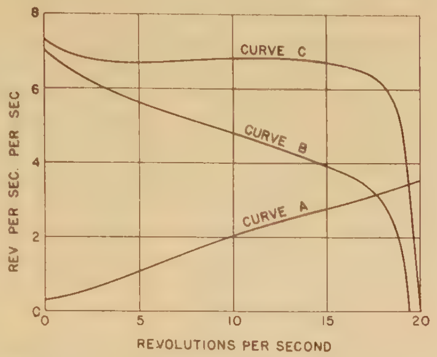

**Figure 5. Acceleration and deceleration curves derived from the curves of figures 3 and 4**

Curve *A*—Deceleration versus speed in the deceleration test

Curve *B*—Acceleration versus speed in the acceleration test

Curve *C*—Electrical torque versus speed

## Curves

Figure 2 shows the distance-time and the velocity-time curves of the $7^1/_2$-horsepower 1,200-rpm 60-cycle motor in the deceleration test. The motor was run at overspeed by supplying power to its stator at about 100 cycles. In figure 3 the same data are used to plot the velocity-distance curve. It is believed that some of the waviness of the curve is due to fluctuations in the frequency of the supply used to drive the synchronous clock. Figure 4 shows the distance-time and the velocity-time curves of the same motor when accelerated from rest by applying three-phase 60-cycle power to the stator. The voltage was about 16 per cent of rated value. The power was applied at the time $t$ = 0.002. The apparent delay in starting in this case amounts to about 0.5 seconds. It is probable that the curve should not plunge into the axis at this point but should contain a reverse bend which would bring it over through the origin. It is also probable that the transients causing this apparent delay have decreased the slope of the curve near the origin so that the torques calculated for the lower speeds are too low.

Curve *A* of figure 5 shows the deceleration as calculated from figure 3, curve *B* shows the acceleration as calculated from figure 4, and curve *C* shows the sum of the ordinates of *A* and *B* and gives the speed-torque curve of the motor. This speed-torque curve of the motor is redrawn in figure 6 in combination with curves showing current and power input. The inertia, spring constants, and damping of the instruments used to measure the current and power have undoubtedly affected the readings near zero speed since power was applied at that time. A slight effect may also be present at the higher speeds but except near zero speed the pointer movements were so slow that errors due to this should be negligible.

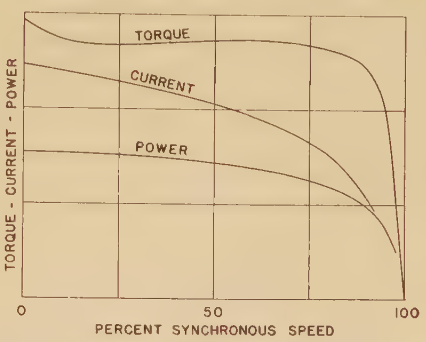

**Figure 6. Complete starting characteristics of the $7^1/_2$-horsepower 6-pole motor**

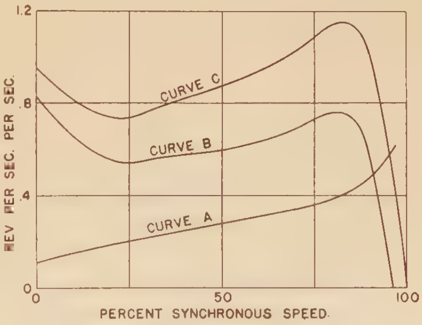

**Figure 7. Deceleration, acceleration, and torque curves from the tests on the five-horsepower 4-pole motor**

In figure 7 are shown the curves obtained in tests on a five-horsepower 1,800-

rpm 60-cycle motor. In this case only 60-cycle power was available and the deceleration test was started from approximately 1,800 rpm. The sharp rise in the deceleration test curve *A* at the higher speeds is undoubtedly due to the iron losses introduced by the trapping of the magnetic field by the rotor. In determining the combined curve, curve *C*, this sharp rise has been disregarded. The acceleration test on this motor was made by plugging it on the line at full-speed reversed rotation instead of starting it from rest. The errors due to transients at the start have thus been eliminated. For this motor dynamometer tests were available in which starting torque, pull-out torque, and the minimum torque between these two had been determined. The ratios of these torques as determined in these tests and as determined in the dynamometer tests checked within about two per cent. An agreement as close as this was somewhat unexpected considering some of the known errors and the widely different voltages used.

## Conclusions

These tests would indicate that the method is quite usable and that the results should be quite satisfactory if the proper precautions are taken. The apparatus required and its costs are relatively small if the phenomena investigated are not of too high speed. With further refinements and the use of stroboscopic cameras, giving finer subdivisions of time and distance, higher-speed phenomena may be investigated, with, of course, an increase in the cost and the complexity of the apparatus.

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# A Variable-Register-Ratio Watt-Hour Meter

By G. R. SHUCK
MEMBER AIEE

AS is generally recognized, electrical energy is a commodity, the sale of which should be subject to the same economic laws that apply to other commodities. The two most important economic laws which regulate the sale price are (1) the law of diminishing costs, and (2) the law of supply and demand.

The first of these laws is partially applied in our present system for metering electrical energy, the so-called block system charging a high price for the first block of energy, a lower price for the next block, and a still lower price for the third block, the whole schedule being equivalent to a lower price per kilowatt-hour for greater consumption.

The second law justifies a higher price when the commodity is scarce or the demand is great, and a lower price when the commodity is plentiful and the demand the least. This law has an application in the 24-hour load cycle of an electric-utility company. The ever increasing peak load of the period between 4 p.m. and 9 p.m. indicates a greater demand and a limited supply, justifying an increased price. The period from 12 midnight to 5 a.m. indicates little demand and an unlimited supply, justifying a decreased price per kilowatt-hour.

Unfortunately, our present method of measuring energy with watt-hour meters does not and cannot supply this second law of economics. The utility rate makers do, however, recognize this law and are applying it in part to some schedules, such as domestic water heating, through the medium of off-peak time switches, carrier-current control, flat-rate schedules, and an allowance of a specific number of kilowatt-hours for water heating in billing.

Although water heating is especially applicable to off-peak control, owing to the heat-storage capacity of water, other loads, both domestic and commercial, could in part be kept off-peak, particularly if there was some incentive for the consumer to do so.

The practice of cutting off water heating loads during peak hours is not altogether satisfactory and is not a logical long-run policy for the utility companies to adopt, because it is only partially effective and does not apply to all shiftable loads.

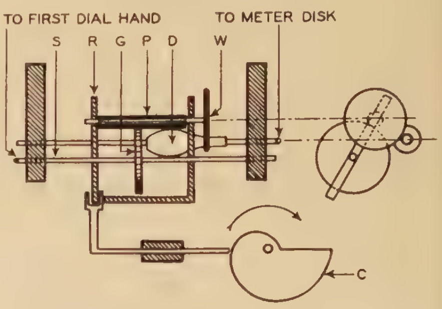

Figure 1

Rather than go to the expense of utilizing schemes for cutting loads off the peak, requiring additional wiring, meters, and timing devices, would it not be more logical to develop some metering system which will automatically take into account this second law of economics? These loads may be left on the system at all times, subject to a higher rate during the daily load cycle when energy is scarce and the demand great, and subject to a lesser rate when the energy is plentiful and the demand least. The consumer may himself apply automatic time switches on his load, or control them manually or not at all, as he chooses.

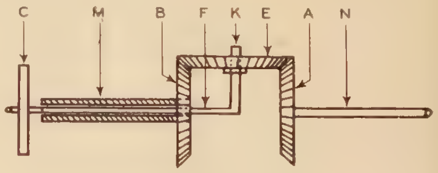

Figure 2

In order to investigate the possibility of applying the law of supply and demand in the metering of electrical energy, the writer, in the University of Washington laboratories, constructed a metering unit from a standard watt-hour meter, which will be called in this paper a variable-register-ratio watt-hour meter.

The variable register ratio is obtained by introducing in the registering train of gears, a drum, and wheel. The position

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of the wheel with respect to the drum is changed during the day by means of a timing unit.

The shape of the variable-diameter drum should be such that the meter registers more slowly during off-peak hours. In general the shape of the drum should correspond to the daily load curve.

Figure 1 is a schematic drawing of that part of the registering train which has been altered. The drum *D* is mounted on one of the shafts of the registering train of a standard watt-hour meter. The wheel *W* and pinion *P* are mounted on a carriage rack *R*, the latter arranged to slide longitudinally as well as turn on shaft *S*. The gear *G* solid on shaft *S* meshes with the long pinion *P* with the carriage in any position. The motion is transmitted from the meter disk through drum *D* to wheel *W*, pinion *P*, gear *G*, to the first dial hand.

The rack *R* is moved to the left along shaft *S* by means of the cam *C* and a push rod, and returned by means of a spring when released by the cam. The forward motion takes place in a little less than 24 hours, the return motion in about five minutes, the complete cycle in exactly 24 hours.

The cam *C* is rotated at one revolution per day by means of a timing unit shown in figure 2. Gear *B*, mounted solid on the hollow shaft *M*, is driven by a synchronous clock at two revolutions per day. Gear *A*, mounted on shaft *N*, is driven in the same direction by an ordinary hand-wound clock at two revolutions per day. The gear *E*, meshing with both gears *A* and *B*, rotates on shaft *K* and revolves with shaft *F*, the latter passing through the hollow shaft *M*. The cam *C*, also shown as *C* in figure 1, is driven by shaft *F*. If either gear *A* or *B* rotates while the other is stationary, the shaft *F* is caused to rotate one revolution per day.

In operation, the synchronous-motor clock drives the shaft *F* and cam *C*, while the hand-wound clock and gear *A* are stationary. In the event of a power interruption, the synchronous-motor clock stops, and the hand-wound clock starts up and drives shaft *F* until the power again comes on and the synchronous motor resumes its duties. The hand-wound clock is designed to start or stop automatically by means of a very small electromagnet which controls the motion of the balance wheel of the clock.

In order to discuss the application of this metering system to a schedule, the 24-hour day may be divided into periods such as normal, off-peak, and peak periods. The normal periods may, for example, be assumed to be from 7:00 a.m. to 4:30 p.m., and from 6:30 p.m. to 11 p.m.; the peak period from 4:30 p.m. to 6:30 p.m.; and the off-peak period from 11 p.m. to 7 a.m.

The diameter of that part of the drum corresponding to the normal periods will be such as to cause the watt-hour meter to register true kilowatt-hours. The diameter of that part of the drum corresponding to the peak period will be greater, causing the meter to register more than the true kilowatt-hours. The diameter of that part of the drum corresponding to the off-peak period will be such as to cause the meter to register less than the true kilowatt-hours.

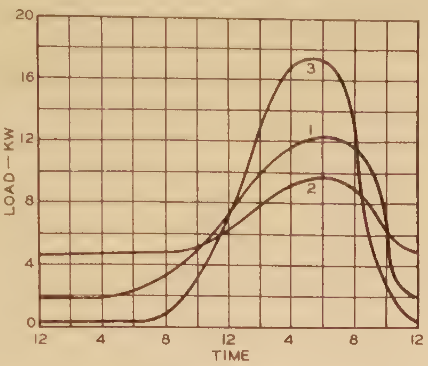

Figure 3. Customer-load curves

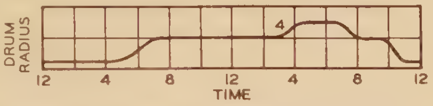

Figure 4. Variable-register-ratio drum radii

Obviously any consumer cannot be expected to have a 100 per cent load factor. He is entitled to use a certain amount of energy during peak hours, and is also expected to use some energy during off-peak hours. The average consumer may be assumed to have a normal load curve, just as the power consumer is expected to maintain a normal power factor within reasonable limits. For purposes of discussion load curve 1 (figure 3) may be considered to be a normal load curve.

The peak and off-peak diameters of the drum may be so calculated that, during a 24-hour period, the variable-register-ratio watt-hour meter, equipped with this drum, will register the true kilowatt-hours of a normal load. That is, a consumer having a normal load curve would have the same kilowatt-hour registration during the month as he would have if his load were metered by a standard watt-hour meter. Curve 4 (figure 4) shows the shape of such a drum. Curve 5 (figure 5) shows the registration of the variable-register-ratio meter for load curve 1 (figure 3) indicating a total registration of 192 kilowatt-hours.

Assume that the consumer has a load curve 2 (figure 3) equal in kilowatt-hours to the normal load curve 1, but showing less peak and more off-peak load. The actual registration curve of the variable-register-ratio meter is shown in curve 6 (figure 5) giving a total daily registration of 172 kilowatt-hours.

Assume the consumer has a load curve 3 (figure 3) equal in kilowatt-hours to the normal load curve 1, but showing more peak load but less off-peak load. The actual registration curve of the variable-register-ratio watt-hour meter is shown in curve 7 (figure 5) giving a total registration of 218.

These curves show that a given number of kilowatt-hours will give different registration, depending on *when* the energy was used.

In some two-rate schedules involving large blocks of power the maximum demand is determined by a graphic recording wattmeter, and the charge per kilowatt of maximum demand varies, depending on when the maximum demand occurred, whether off-peak or on-peak. In two-rate schedules involving small blocks of power the indicating maximum-demand register is used. This method gives no indication of the time of day the maximum demand occurred. If a maximum-demand attachment were installed on the variable-register-ratio watt-hour meter, it would automatically register a higher or lower indication, depending on the time of day the maximum demand occurred.

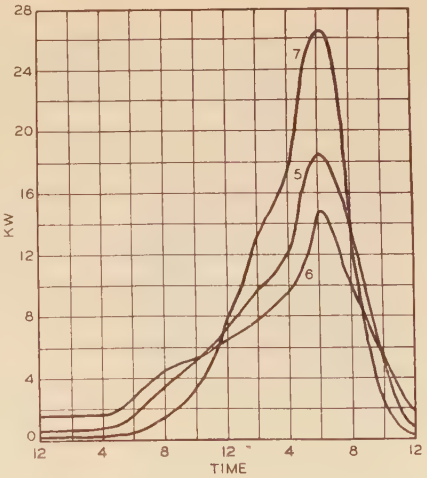

Figure 5. Rate of meter registration

The variable-register-ratio watt-hour meter may be used in a different way by having two registers, one a standard dial, the other a variable-register-ratio dial. The standard dial registers the true kilowatt-hours as any other standard meter. The variable-register-ratio dial gives the modified registration as already explained. The ratio between these two readings gives a modifying factor $K$ which may be used in billing the true kilowatt-hours.

Assume the consumer has the normal load curve 1 (figure 3). Both dials will indicate the same, namely 192, and the factor $K$ will be $^{192}/_{192} = 1$. Assume the consumer has load curve 2. The standard dial will again register 192, but the variable-register-ratio dial will register 172. The factor $K$ will be $^{172}/_{192} = 0.895$. Assume the consumer has load curve 3. The standard dial will register 192. The variable-register-ratio dial will register 218. The factor $K$ will be $^{218}/_{192} = 1.135$. The factor $K$ obtained each month is a measure of *when* the energy was used and may be used as a modifying factor in billing the true kilowatt-hours.

The meter constructed in our laboratories (figure 6) consisted of parts of other meters assembled together into a working unit to test the general method, and is essentially a crude instrument compared to one which would be designed and constructed by a manufacturing company. However, some information was obtained which leads to the following conclusions.

1. A variable-register-ratio watt-hour meter can be constructed of sufficient accuracy and low cost to compare favorably with the present methods of controlling off-peak loads, and at the same time to have more universal application.

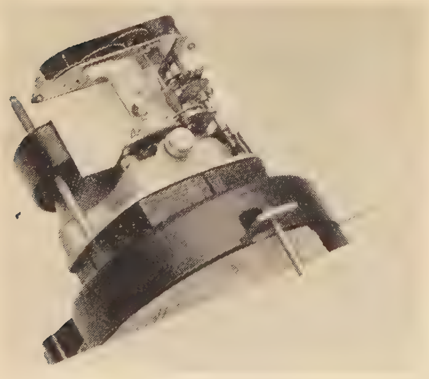

Figure 6

2. Tests were conducted to show the accuracy of transmission through a drum and wheel. The ratio between the frictional torque at the wheel and drum, and the torque required to drive the registering train was found to be three to one, showing a sufficient factor of safety in regard to the wheel slipping on the drum. A proper design and choice of material could, no doubt, increase this factor many fold.

3. The timing device should consist of a synchronous-clock motor with an auxiliary hand-wound or electric-wound clock designed to run not more than 24 hours, since power interruptions sum up to be far less than 24 hours during one month. It was found by test that the smallest type of synchronous motor produced 100 times as much torque as was necessary to rotate the cam.

4. The design of the unit should be such that the drum of the variable-register-ratio dial can be removed and another inserted without dissembling the registering train, to conform to any desired rate schedule. If it is desirable to convert the variable-register-ratio meter into a standard watt-hour meter it is only necessary to slip in a cylinder of proper diameter, or to replace the entire register with a standard registering dial.

5. In view of the probable objection on the part of the rate commissions that the variable-register-ratio meter does not actually register kilowatt-hours at all times, the second method of the two outlined in this paper would be more acceptable, the meter being used to obtain a monthly modifying billing factor.

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# Trends in the Design and Arrangement of Electrical Equipment in Hydraulic Power Plants

By C. C. WHELCHEL
MEMBER AIEE

DURING the last ten years there has been a considerable development of water power resources in this country. Many different organizations have participated in the design of these projects, and many contributions have been made to reduce the first cost, improve the over-all efficiency, and reduce the cost of operation. A brief review of those trends which represent the greatest changes, or have provoked the most discussion, may be of interest at this time. On many of them there is no unanimity of opinion. The reader may disagree with some, he may even question whether others represent general trends at all; nevertheless, the writer will try to give them without either commendation or condemnation, and he would not be entirely candid if he did not say that some looked rather foolish to him at first. It should be emphasized that this paper will discuss only those features which have been changing, or have provoked discussion; many things which are of much greater importance to the station may therefore be mentioned only briefly, if at all.

## Powerhouse

A number of semioutdoor type of generating stations have been built in which the conventional powerhouse superstructure was omitted. In this design the generator-room floor becomes the station roof, the generators being protected by a concrete or metal housing. An outdoor gantry crane is usually provided for removing the waterwheel and generator parts to one end of the station, where they may be lowered through a hatch to the inside repair bay below. The layout of the generating units and their auxiliaries is arranged so that practically all operation in connection with the equipment will be below the generator deck, where complete protection is obtained. There is a considerable difference of opinion as to the true over-all saving with this type of plant, particularly where the extra cost of installation and maintenance is taken into account. If experience demonstrates the absence of operating and maintenance difficulties, they may be more generally adopted in the future.

In the past, it has been the general practice to locate the generators in the powerhouse above the maximum expected flood waters, and in many cases this has resulted in an expensive structural design, because of the distance between the waterwheel and generators. In several

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recent projects, it was found that the most economical arrangement was to place the generators as close to the waterwheels as ordinary considerations would allow, and protect them from flood waters by building a waterproof powerhouse without windows. This type of station naturally results in an indoor design, since the walls are essential for flood protection, and only a roof is necessary to enclose it.

## Generators

Further economy in power-plant design has been achieved by an increase in the size of the generators and waterwheels over those which would have been considered practicable a few years ago. Operating efficiency has been improved by the increased use of the adjustable-blade turbine for low-head developments. Although these trends principally represent an advancement in the design of hydraulic machinery, they, of course, affect directly the generating equipment. The largest unit in physical size at a particular speed which it is possible to build economically at the present time has not been reached, but it has been closely approached. The limiting factor in waterwheel-generator design is usually the mechanical stresses at runaway speed.

There has been very little change in the structural design of waterwheel generators in the last few years. Fabricated construction continues to be widely used. Partly because of the accuracy with which the strength of fabricated rotors can be predetermined, and partly because of the expense of building up and tearing down again to meet shipping limitations, particularly on the larger size units, overspeed tests are seldom made at the factory.

Overhung or umbrella type of generators with one guide bearing have been installed in a number of stations. Such generators show a slight saving in first cost over the conventional two-guide bearing type. There is, however, an upper limit in speed and physical size beyond which it is not practical to go. Owing to the lack of an upper-guide bearing on the generator, these machines are tested with the waterwheel attached. The design therefore is more difficult to test and does not lend itself readily to the investigation of vibration and other possible troubles.

The highest voltage waterwheel generator built so far in this country is 16.5 kv. Studies have been made on the larger units for voltages of 23 and 34.5 kv with the result that a more conservative and economical design was obtained with a generator voltage of 16.5 kv or less, and a step-up autotransformer. This combination is as efficient as a generator wound for 23 or 34.5 kv.

The advancement in the knowledge and appreciation of system stability has generally resulted in a more careful study and selection of those generator characteristics which affect stability.

A fuller understanding of the general operating advantages of amortisseur windings in waterwheel generators has resulted in their incorporation in a number of units. The principal advantages are: the reduction of overvoltages in the stator winding resulting from unbalanced faults on the generator, particularly on unloaded machines coupled to capacitances such as transmission lines; the effective reduction in oscillations of generator-output kilowatts occasionally experienced on machines which are connected to their loads through high resistance circuits; and a minor aid in system stability by reducing the magnitude of the rotor oscillations.

Experience has shown that even though water-power developments are usually located in rural districts, the air is not free from impurities which lodge in the generator and interfere with the effective cooling of the machine. For this and other reasons the closed ventilating system, using surface air coolers, has been adopted for most of the recent generators above 5,000 kva. In addition to the longer expected insulation life, the closed system reduces station noise and provides increased fire protection. In some installations it permitted a more economical powerhouse, since provisions for large air intake and discharge openings in the building were not required.

On very large generators, where the stacked height is sufficient, the cooler sections have generally been arranged vertically around the periphery of the generators. On the comparatively small machines, where the stacked height is so short that a vertical arrangement around the periphery would be expensive, the sections have been located parallel to the floor, and on the side of the unit for vertical machines, and underneath for horizontal units.

Of the hydraulic generators which have been provided with surface air coolers, less than half are arranged to discharge air to heat the power station. The trend is in the direction of permanently closing the generators, and deriving station heat from some other source, because obviously any departure from the closed system reduces the effectiveness of that system.

Although generator fires are rarer now than ever before, carbon-dioxide fire protection has been provided on many of the larger generators, because of its effectiveness on the closed ventilating system as compared to the open system.

In the larger-size generators which require extensive disassembly for shipment, it has become the general practice to make the electrical tests as well as overspeed tests after installation.

## Excitation Schemes

The excitation scheme, used almost exclusively in the last few years on generators rated 3,750 kva and above, employs direct-connected main and pilot exciters, and a high-speed individual rheostatic voltage regulator operating in the main exciter field. A main a-c generator-field rheostat is not required, and in a number of instances the armature of the main exciter is permanently connected to the generator field without a field switch. No provision is made for paralleling exciters.

The operating simplicity of the direct-connected exciters has a very strong appeal. This system generally has the advantage of lower cost, considering in one case a shaft alternator and a motor generator set, and in the other case a direct-connected exciter plus a small step-down power transformer to serve the machine auxiliaries otherwise served by the shaft alternator. Beyond this difference in price is the additional switching equipment, such as circuit breakers and switchgear panels, not to mention increased wiring and cable connections.

Because of the low outage record of direct-connected exciters, the complications introduced by trying to provide spare excitation in what is otherwise a unit system, and a station design which contemplates the outage of a complete generating unit without adversely affecting operation, the spare motor-generator exciter set has been omitted in a number of stations.

In many stations, advantage has been taken of the possibility of allowing considerable variation in generator voltage in order to obtain better system-voltage regulation. In such stations line-drop compensation has usually been incorporated in the generator voltage regulators. In a properly co-ordinated generator voltage regulating system there is no conflict between line-drop and cross-current compensation.

## Governor Flyball Drive

One of the early steps taken to free the governor flyball drive from the physical limitations of a belt was to provide a flyball motor and drive it from the main generator terminals through small transformers. This type of drive was found to be satisfactory in most instances, although it has the disadvantage of tending to cause the governor to follow system frequency rather than generator frequency during those rare cases when the main unit twists out of step with the system due to instability.

Although this condition has occurred very rarely in practice, the desirability of eliminating it was early recognized. The next source of power used was obtained from slip rings on the pilot exciter. Where steps were taken to obtain proper co-ordination in design between the governor motor and pilot exciter, this scheme has operated satisfactorily. Where this was not done, trouble has been experienced in some installations due to a very sensitive governor head along with slight phase-shifting of the pilot exciter flux with respect to the shaft of the main unit, with the result that the governor did not see true shaft speed at all times.

A permanent magnet generator directly mounted on each unit is the latest source of power supply for governor flyball motors, and is the system which has generally been used in the last few years.

## Circuit Arrangements

Hydroelectric-generating-station switchgear shows a decided tendency toward simpler circuit layouts including the elimination of generator oil circuit breakers and low-voltage busses, resulting in a considerable saving in cost, as well as a greatly simplified station design.

The so-called unit system has been widely adopted. The simplest case with this scheme is to have one generator connected to its own individual transformer bank. In the earlier installations an oil circuit breaker was installed between the generator and transformer primarily for synchronizing purposes. The present oil circuit breakers of all voltages have closing speeds sufficient for synchronizing on the high-voltage bus, so that in the more recent installations the breaker between the generator and the transformer has been omitted.

Some stations have used a modification of the unit scheme in which two generators are connected to one transformer bank, each generator having its own low-voltage breaker in order to be able to synchronize or remove one generator from service without affecting the other.

Many operating engineers have concluded that the unit scheme with its omission of the low-voltage bus represents practically no sacrifice in over-all station reliability or flexibility. Although this scheme is open to the criticism that, if a generator fails and at the same time a transformer normally connected to another generator also fails, the output of the two machines is lost, operating records show that such a contingency is very unlikely to occur. Furthermore, few plants are designed on the basis of two simultaneous failures, since their cost would be prohibitive.

## Switchgear Equipment

Although the simpler circuit layouts now so prevalent in hydro stations have appreciably reduced the number of low-voltage oil circuit breakers, nevertheless many stations still require large-interrupting-capacity breakers in addition to the smaller ones for controlling station-service power.

In many of the more recent projects, these breakers, their disconnecting switches, busses, etc., are enclosed in complete factory-built metal structures. Metal-enclosed busses from the generator terminals to the power transformers are also being used.

The increasing use of metal-enclosed gear is attributed to the more general appreciation of its economy and safety features. By using this equipment, station planning has been simplified by eliminating the time and expense in detail designing and co-ordination which is required where cell-mounted equipment is used. Savings in building cost have been realized in many instances, because this type of gear saved floor-space and headroom. As a rule, metal-enclosed gear has been found to cost less installed than other types in which equal precautions have been taken to preserve service continuity.

Many refinements in oil-circuit-breaker design have been made in the last few years. More effective means for controlling the interruption of the arc has permitted smaller oil circuit breakers for the same voltage, current, and interrupting rating. Faster operating mechanisms are now being used to speed up the tripping and closing times, thereby reducing system disturbances. In the high-voltage field, oil circuit breakers rated 287 kv and, having a clearing time of three cycles, have been installed. Inasmuch as these breakers were of very low oil content, they evidenced the trend toward low-oil-content breakers.

Metal-enclosed air circuit breakers or contactors are extensively used for controlling station service power at 550 volts or less. This equipment permits a still further reduction in fire hazard and its compact construction results in a saving in space and installation expense.

## Control Boards

The tendency is toward the so-called duplex board with control, indicating instruments, etc., on the front panels, and relays, meters, test blocks, and similar equipment on the back panels. In some of the larger power plants, supervisory type of control has been mounted on duplex panels. Such control eliminates some of the wiring complexities, permits a smaller switchboard control room, and makes it possible for the operator to follow station conditions more readily since the essential information is concentrated in a relatively small space.

The advantages of supervisory control are secured by locating cubicles adjacent to the generators with which they are associated. The duplex switchboard located in the main control room has supervisory control over these cubicles. Only those indications and controls which are required for station operation are provided on the duplex board, thereby reducing the number of instruments and devices, and the amount of interconnecting control cable. A signal system is used to indicate abnormal operating conditions, which in some instances may require the attention and assistance of a generator floor man. In an emergency the generator floor man can take over the operation of the unit at the generator cubicle.

Automatic synchronizing equipment has been provided to a greater extent than in the past, because the operation is accomplished smoothly and without the switchboard operator's neglecting other important duties at that time.

## Station-Service Power

The supply of station-service power, like excitation schemes, has run a varied and interesting course. Like excitation with which it has at one time or another been closely associated, the trend has been toward greater simplicity, influenced perhaps as much as anything by a careful re-examination of the basic service requirements of the individual devices that make up the station-service load. After doing the same thing the same way for a few years, additional experience gained in that time frequently demonstrates that the requirements are not so severe as they had been assumed, or else the improvement in apparatus permits a simpler solution. Such has been the case with station-service power.

With the use of direct-connected exciters instead of motor-generator exciter sets, the principal reason for the shaft auxiliary generator was eliminated. The simplest and most economical system for obtaining station-service power, which at the same time possesses a high degree of flexibility, has been obtained by connecting a small step-down transformer to the generator leads, either directly or through a disconnecting switch. This system has been widely adopted in the last few years, particularly in stations without a low-voltage bus.

With this scheme the auxiliaries intimately related with each generating unit are fed from the transformer connected to the terminals of that generator. This transformer usually supplies a low-voltage bus from which emanate the leads to the various unit auxiliaries, such as governor oil-pump motor. To give duplicate service to this bus for emergency or starting up the station, power is fed from an adjacent bus, a house generator, or a high-voltage step-down station-service transformer bank.

Present indications are that the unit station-service-power scheme may be used in the future, even in stations with a low-voltage bus, since it permits the elimination of an expensive high-interrupting-capacity switch position.

## Grounding and Protective Equipment for Generators and Transformers

It is difficult to discern any particular trend in generator-neutral grounding and relay protection on units connected to low-voltage busses from which feeders emanate. Such generators are either solidly grounded or else grounded through a neutral impedor. The limits are, on the one hand, a sufficiently low value to stabilize the system neutral, and on the other, high enough to minimize damage resulting from faults.

In stations employing the unit system, where each generator is directly connected to the delta side of its own step-up transformer, the relaying and grounding trends have been interesting. In many stations, the generator neutral is solidly grounded. This permits the generator differential relay to protect the maximum amount of the generator winding on phase-to-ground faults, but on the other hand grounding the neutral solidly has the disadvantage of permitting the maximum amount of fault current.

Damage resulting from a fault, however, depends on duration as well as magnitude. In following the approach of reducing fault duration, high-speed balanced-beam differential relays operating in one or two cycles have been used in a number of stations, instead of induction-type relays having six- to eight-cycle operating times. This reduces the overall fault-clearing time from approximately 14 cycles to 9 cycles where the generator-neutral breakers are used to unground the machine.

Because of the increased cost of the very special current transformers now required to provide high-speed generator differential relaying and the comparatively small gain in time in extinguishing the arc, there is a trend back to induction-type relays. This trend is perhaps further influenced by the feeling that if damage from line to ground faults is the principal reason why generator differential relays have been speeded up, then the more direct attack on the problem is to insert an appreciable amount of resistance in the generator neutral, or unground it entirely, as has been done in some stations. In the latter case, a ground detector which signals the station operator, but does not trip the unit, is usually employed. This permits temporary operation until a shutdown can be conveniently arranged.

There has been some interest in high-speed transformer differential relaying, but in the case of power-transformer protection, the problem is more difficult than in the case of generator-differential protection, for not only must instrument transformers be matched with bushing transformers, but even more important, provision must be made to prevent false tripping during magnetizing inrush periods. Despite these difficulties installations of high-speed transformer differential relays have been operating quite satisfactorily. The choice between high-speed and induction-type percentage differential relays is largely dictated by stability considerations.

There has been a trend toward the increased use of bus differential protection where there were large concentrations of power because the preservation of service continuity requires the speedy clearing of the large resulting fault currents. From the protective standpoint the presence of large fault currents causes current-transformer saturation that tends to operate the differential relays during faults external to the bus. The relay current in the case of an external fault differs from that arising from a bus fault, in that it has a large harmonic content. The recognition of this difference has led to the development of a harmonic-restrained high-speed bus differential relay, which will undoubtedly find increasing use in the future.

In the past, generators feeding through step-up transformers were generally believed to be immune to lightning due to the fact that the transformer bank would act as a buffer against incoming waves. It is now known that this is not entirely true, and consequently generator lightning-protective equipment is commonly installed. Experience has indicated that a relatively small investment in properly selected equipment will provide a degree of protection that will result in a material reduction of the possible lightning stresses imposed on rotating machines and contribute to an appreciably increased security against faults due to lightning-impulse voltages.

## Outdoor Substations

The arrangement of the high-voltage equipment at a hydro station is largely influenced by the topography of the site and the location of the powerhouse. In those projects where the outdoor switchyard is separated more than a few hundred feet, the general practice has been to locate the step-up transformers adjacent to the powerhouse, and conduct the power to the outdoor switchyard by means of overhead high-voltage lines.

Outdoor substations at 66 kv and above are commonly shielded by overhead ground wires which extend out over each line for at least half a mile. The use of overhead ground wires has increased the height of the outdoor structure somewhat and requires slightly heavier steel to carry the additional load, not only in dead weight, but also to carry the take-offs on the outgoing lines. These items represent only a small addition to the total cost of the station.

Shielding of outdoor substations practically eliminates the possibility of direct strokes nearer than half a mile from the substation, thereby limiting the incoming surges to a value that a lightning arrester can handle. In spite of a considerable discussion during the past few years of the real merits of plain gaps versus lightning arresters for apparatus protection, arresters continue to be in very general use. This is for the reason that gap settings which give a degree of protection comparable to that of lightning arresters result in more dynamic flashovers than can ordinarily be tolerated.

## Power Transformers

The trend in the design of power transformers continues to be in the direction of improvement in the dielectric strength and refinements in mechanical construction. Much attention has been given in the last few years to the study of insulation co-ordination, resulting in improved insulation strength to resist lightning, and the proper distribution of impulse stresses throughout the transformer winding obtained, for example, by the use of shielding.

There is a trend in the larger size transformers toward the use of the gas-sealed unit, wherein the space between the oil and the cover is filled with dry nitrogen gas. In addition to providing a seal against the entrance of oxygen, moisture, dust, etc., some operators feel that the fire hazard is less, because the oil level is below the transformer cover. The outstanding contribution from the design standpoint toward minimizing the fire hazard in power transformers, however, results from the use of a noninflammable liquid instead of transil oil. Indications point toward an increased use of such transformers in the future.

The general tendency in this country has been to install single-phase transformers to form three-phase banks, even where three-phase transformers were practicable from a physical standpoint. A re-examination of this problem from the standpoint of outage, handling, and reliability, indicates an increased interest in three-phase units.

Strange as it may at first seem, several recent large hydro stations have installed self- or forced-air-cooled transformers. The elimination of the cooling water system has influenced their selection to some extent. Another consideration was the ability to obtain outputs above the self-cooled rating with forced air. The latter is directly attributable to the generator rating and temperature rise. Most generators rated 11 kv and above use class *B* insulation, with class *A* temperature rise. Operating experience with such a design indicates a longer life and one capable of carrying some emergency overload. This requirement may arise under the most favorable hydraulic conditions, since at that time the capacity of the waterwheel may be in excess of the normal generator rating. The air-pressure cooling equipment on the power transformer provides an economical means of obtaining transformer capacity to match the maximum generator output.

Step-up transformer high-voltage-neutral grounding shows a trend away from solidly grounding in the direction of grounding through an impedance, and in a recent installation at 220 kv this impedance was a Petersen coil. The experiences with these coils in this country in the last few years indicates a more general acceptance of this device for improving system performance.

Because of the desire to obtain noninflammability of the liquid, as well as to eliminate explosions of the arc-formed gases, there is an increased use of noninflammable synthetic insulating oil in station-service transformers, particularly those installed in the powerhouse.

## Summary

From the foregoing discussion, it has been seen that the outstanding trends in the design and arrangement of electrical equipment in hydraulic power plants, with but a few exceptions, are toward greater simplification, reliability, and lower first cost. Inasmuch as fixed charges constitute the major portion of the cost of hydro power, a reduction in first cost affords the principal means for securing a reduction in the cost of water power.

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# Discussion

**J. H. Foote** (The Commonwealth and Southern Corporation, Jackson, Mich.): This paper covers the subject in a comprehensive manner and gives a good general picture of some of the developments in the design of hydraulic plants and the equipment which goes into them. Many of the types of design and the features outlined in this paper have been used successfully by our associated companies for a number of years.

### POWERHOUSE

In 1925, we designed and built a hydraulic power plant, utilizing the semioutdoor type of construction, with two 1,060-kva units. This plant is of the automatic variety and this type of construction has proved satisfactory from an operating standpoint.

### GENERATORS

We have also utilized the enclosed type of air-cooling system for the generators of one of our newer large hydraulic power plants with satisfactory results.

It might be pointed out that the testing of umbrella-type generators in the field, with the waterwheel attached, may be of small consequence if both units are of the same manufacture, but if different manufactures are involved, it may be very important to be able to test the units individually.

### EXCITATION SCHEMES

Direct-connected main and pilot exciters have been used on our hydrogenerators since 1924 with satisfactory results. In fact, direct-connected exciters have been employed without spare exciters or excitation busses since 1905 with success. No exciter failures have been experienced, and the practice of not providing spare sources of excitation has not caused us any difficulty. It is felt that the chief advantage of using the pilot exciter is that greater stability of the excitation system is obtained.

It has been noted with interest that in certain cases field switches have been omitted. We have successfully operated four generators so connected since 1922. In many of our generator-overvoltage protective schemes, the generator voltage regulators are depended upon for overvoltage protection. However, as a matter of backup protection, or where voltage regulators are not installed, facilities have been provided for tripping the field switch in case the generator voltage reaches an excessive value under runaway conditions. Where no main field switch is used, we have had success in using a small air circuit breaker to cut in resistance in the exciter field or to open the exciter field as a last resort. It also seems desirable to remove the excitation from the machine in case the differential protective equipment functions. A field switch in the exciter field seems to function satisfactorily in the absence of a main field switch.

The necessity of providing special current transformers for high-speed differential relaying is a problem requiring further detailed investigation so that a better understanding may be had of the performance of current transformers during the early transient stages of a fault.

### GOVERNOR FLYBALL DRIVE

The use of an electrical drive for the governor has been a very desirable development, but our experience indicates that serious trouble may be experienced if the drive receives its energy from slip rings on the pilot exciter, especially if the generator is equipped with a voltage regulator. Permanent-magnet generators provide a very satisfactory source of supply for governor motors.

### CONTROL BOARDS

Our experience with automatic synchronizing equipment indicates that while satisfactory performance can be obtained under steady-state conditions, certain types of equipment may fail to function during transient conditions or emergencies, and it is most needed at these latter times.

**Transactions**

**Papers and Discussions Comprising Pages 83–130 of the 1939 Volume**

# Phase-Angle Control of System Interconnections

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**Synopsis:** This paper describes an application of a new method of automatic control between two interconnected power systems, whereby greater utilization of the interconnection capacity is secured. As the stable limit of the interchange between systems is affected by variations in the magnitude and location of intermediate loads on the respective systems, direct control of the phase angle between systems recognizes such variations and permits a flexible and more stable type of operation including, when desired, maximum transfers of energy. An indication of the 60-cycle voltage from a desired point on one system is continuously transmitted by means of carrier current, to a point on the second system where its phase position is compared with that of the 60-cycle voltage at the receiving point. The output of generating units at the control station is automatically regulated to maintain the phase angle between systems at desired values or within predetermined limits.

THE power systems in the Pacific Northwest have been successfully operated interconnected for many years. In addition to the normal or routine functions, on several occasions these interconnections have been called upon to transfer large blocks of power and energy to alleviate abnormal conditions on one system or another, averting serious power shortages.

Heretofore, the control of the power flow between these systems has been accomplished principally by manual operation. The amount of power which has been interchanged, under some conditions, and between some of the systems, has not approached the stable limit of the interconnections, and manual control has not been difficult. On some of these interconnections, however, experience has demonstrated, as in similar situations in other parts of the country, that because of the time required for communication and manual control of generating units, the interchange had to be regulated to values well within the stable limits, in order to prevent, or at least limit the number of severe disturbances otherwise occasioned by the systems separating due to relay action as stable limits were approached, or actually pulling out of step.

In considering the application of automatic-control equipment for the interconnection between the systems of The Montana Power Company and The Washington Water Power Company, so that a flow of power closer to the stable limit could be safely carried, a new method of control, based upon the phase-angle difference between systems, was conceived and developed. This paper describes the application and the experience so far obtained with this type of control.

## Description of Systems and Interconnection

Figure 1 is a map of the Northwest showing the principal transmission lines of the several interconnected systems.

On The Montana Power Company there is approximately 300,000 kw of hydroelectric generating capacity with 250,000 kw usually in service. The total capacity will be increased to 350,000 kw in 1938. A large part of this generating capacity, and a substantial part of the load served, are both located in the Great Falls area. Many of the larger individual loads served from this system, including hoists, railway, and dredge loads, are of such magnitude and fluctuating character that sudden load changes of from 5,000 to 30,000 kw are not uncommon.

The point of interconnection between The Montana Power Company and The Washington Water Power Company systems is at Burke, Idaho. For a number of years previous, and at the time this application of automatic control was planned, the ability to interchange power between these two systems was limited by the single 110-kv, 170-mile transmission line of the Chicago, Milwaukee, St. Paul and Pacific Railroad Company between East Portal and Gold Creek. The capacity for power flow eastward was variable, depending upon seasonal variations in the Thompson Falls hydroelectric plant output. The second line from Thompson Falls, via Flathead to Anaconda, was added in March 1937, practically coinciding with the installation of the phase-angle control equipment. The purpose of this latter transmission line was to transmit power into Montana during an unprecedented low-water period and to furnish a second channel for Thompson Falls power into the Montana system as well as that from Flathead. At later periods it is contemplated these lines may transmit power to the west.

The Washington Water Power Company system is also served by hydroelectric generation, with approximately 200,000 kw of capacity, most of which is usually in service. A large concentration of capacity and load on this system is in the Spokane area.

The Washington Water Power Company system is in turn interconnected with the system of the Puget Sound Power and Light Company on the west, having approximately 300,000 kw of capacity. To the southwest, Washington is interconnected with the Pacific Power and Light and Northwestern Electric Companies, having an aggregate capacity of 120,000 kw. The Portland General Electric Company, 175,000-kw capacity, and Washington Gas and Electric Company, 30,000-kw capacity, are in turn interconnected with the Northwestern Electric Company system in the Portland area. The Portland General Electric Company, however, is not normally

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The authors gratefully acknowledge the co-operation of their associates in the engineering and operating organizations of The Montana Power Company and The Washington Water Power Company, and particularly of H. L. Melvin of Ebasco Services, Inc., G. E. Heberlein and R. E. Powers of Westinghouse Electric and Manufacturing Company, and S. B. Morehouse of Leeds and Northrup Company, in the successful development and application of this method of control.

operated in parallel with the Northwestern Electric Company when Northwestern is in parallel with other systems in Washington and Montana.

For several years the Long Lake hydroelectric station of The Washington Water Power Company has served as the primary frequency-controlling station for the entire group of systems. Additional frequency-control equipments have been available at the Morony station in Montana and the Ariel station in the Portland area, but have not generally been used when operating interconnected with Washington.

## Operating Limitations With Manual Control of Interchange

From previous operating experience, when transmitting power from Washington to Montana over the original connection, it was known that the systems were likely to pull out of step whenever the power input into the line at East Portal (interchange at Burke, plus Thompson Falls generation, less local load at Burke and line loss) reached values in excess of 50,000 kw. The normal practical operating limit, under manual control procedure, was considerably less, in the order of 40,000-kw maximum, or 35,000-kw average, because whenever attempting to operate at any higher value, the rapid "drifting" of the power flow would reach the pull-out point too often. The usual "swings" in power over this interconnection were approximately 5,000 kw, with occasional swings of up to 15,000 kw.

With the Thompson Falls plant output (40,000-kw maximum during high-water months and 20,000-kw average during low-water months) flowing eastward, the maximum permissible average power flow through Burke, Idaho, ranged from approximately 0 to 15,000 kw. To obtain these average flows, with manual control, it was necessary to place observers at Burke and Gold Creek; the observer at Burke giving very close attention to the meters and promptly reporting excessive loading conditions to the observer at Gold Creek, who would in turn report conditions to the controlling station. Even with these precautions, from one to eight system separations would occur practically each day.

Because of a combination of circumstances, including several successive years of lower-than-normal precipitation and run-off in Montana, it was decided in the fall of 1935 that the capacity of the interconnection would have to be increased and at the same time maximum possible use might have to be made of this interconnection in transferring energy into Montana during the succeeding one or two years. It was decided to build the second transmission line, referred to above, and install automatic control equipment, in order to increase the practical operating limit and the load factor of the interconnection.

## Experimental Tie-Line Load Control

As a preliminary step, an experimental installation was made of automatic tie-line load control, based upon a measurement of the power flow in the 110-kv line at Gold Creek. A carrier-current-telemetering circuit, operating at 20 kilocycles over the private open-wire telephone line, with variable frequency

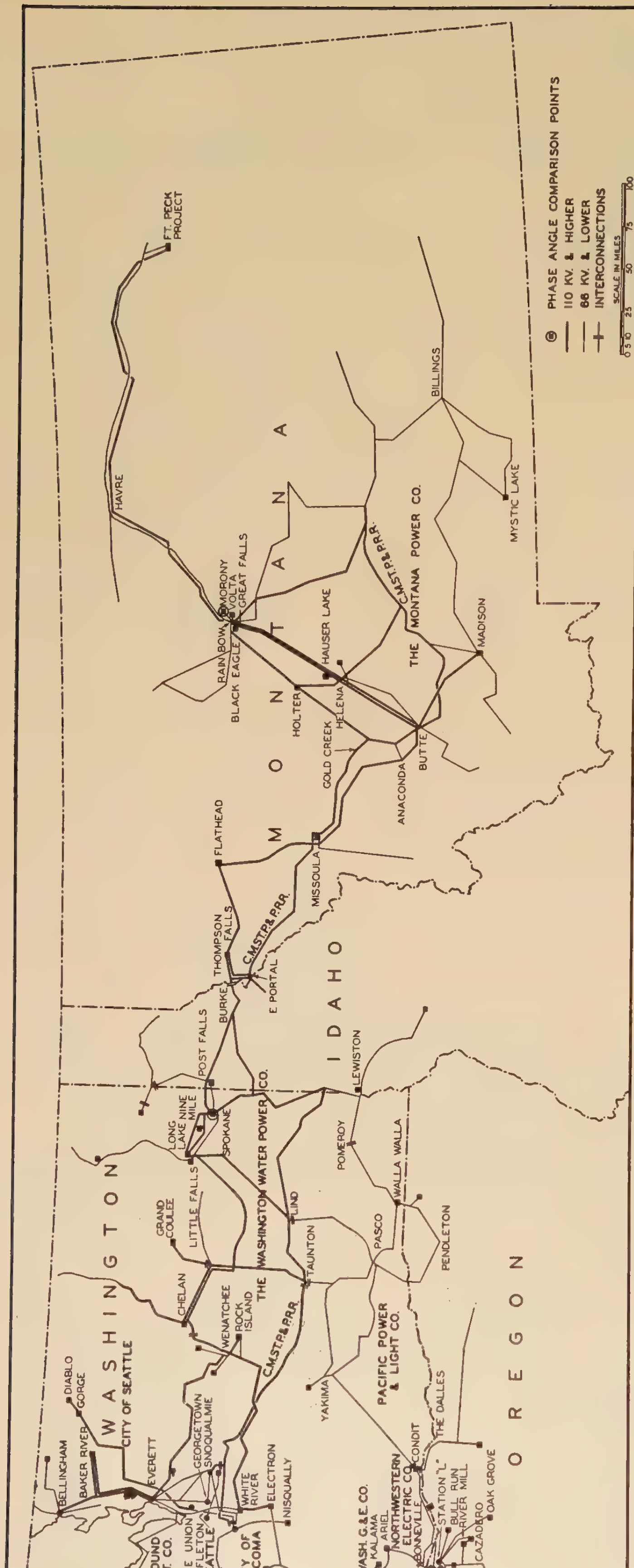


Figure 1. Major electric power systems—Pacific Northwest

modulation, gave an indication at the Morony hydroelectric plant of The Montana Power Company on the Missouri River near Great Falls, Montana, of the power flow in the line at Gold Creek. The automatic-frequency controller installed at the Morony plant was temporarily modified and used for automatic tie-line load control. This type of automatic control gave a definite improvement in the interchange capacity; the permissible average flow through Burke being increased to approximately 21,000 kw, with separations of the systems occurring on the average of only once every two days.

## Conception and Development of Phase-Angle Control

In considering the alternate locations for a permanent installation of a tie-line load measurement and telemetering transmitter, it was recognized that no one location could be chosen where the tie-line load as such could be controlled to any definite quantity over a period of time, and at the same time secure the maximum possible transfer of energy between systems. With only the Chicago, Milwaukee, St. Paul and Pacific Railroad Company line constituting the tie between systems, the power transfer at any point varied considerably due to the nature of the railway load. Not only did the railroad's electric trains have a widely variable demand, but the location of the load along the transmission line varied as the trains progressed from one section to another. Furthermore, these trains employed regenerative braking so that at times, either a part or all of the load actually became generation with a correspondingly variable point of application. This was particularly true along the 110-kv line from East Portal to Gold Creek.

For example, if the tie-line load at Gold Creek were to be controlled, the permissible power flow at this point would be greater when the intermediate-substation loads were light, especially at the Gold Creek end of the line, than when the intermediate loads were heavy. Consequently the control would have to be set for the smaller value of power transfer, to be safely within the stable limit under all conditions, and no advantage could be taken of the greater permissible flow during a large proportion of the time.

Likewise, if controlling the tie-line load at East Portal, for example, the control would have to limit the flow at this point to the amount that could safely be carried when the intermediate loads between East Portal and Gold Creek were light, without taking advantage of the greater permissible flow whenever a large part of the power flowing past this point was being consumed at the East Portal, or other substations near the western end of the line.

It was also recognized that with the planned addition of the Thompson Falls-Flathead-Anaconda circuit, stability limits, division of power flow between circuits, and permissible angular displacements between the systems would change.

Inasmuch as stability is basically a function of angular displacement between systems, it was conceived by the authors that the phase angle itself should be utilized for the control of the interchange, rather than a measurement of the power flow at any one point. It was proposed to transmit, by a continuously modulated carrier-current signal over the transmission circuits, an indication of the 60-cycle bus voltage at a point on the Washington system to a point on the Montana system. The received signal, being an indication of the angular position of the voltage in Washington, would be compared with the phase position of the local Montana 60-cycle bus voltage. Based on a measurement of the phase-angle difference between these two voltages, the output of generating units at the control station selected would be automatically regulated to maintain the phase angle at the desired point or within predetermined limits.

It was thought that phase-angle control might provide several alternate methods of operation, including those shown in figure 2.

Development and application of this method of control involved consideration of the following questions of fundamental importance:

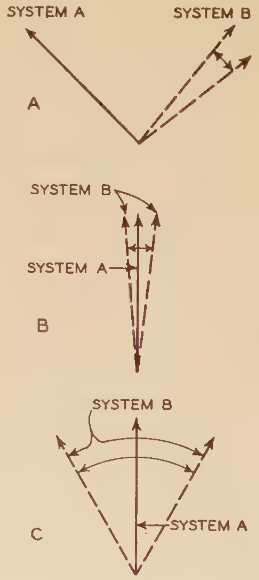
What location should be chosen on each system, for voltage measurement in the determination of the proper phase angle for control?

What phase-angle distortion or attenuation would occur in the carrier-current equipment and transmission channels, from the transmitter input to the receiver output, and what variations would there be in this transmission under different operating conditions?

What would be the effects of outages of lines at any point on the network between the two phase-angle determination points?

Following co-operative studies with engineers of Leeds and Northrup Company and Westinghouse Electric and Manufacturing Company, it was concluded that:

1. The phase angle should be measured between the East Side substation, near Spokane, on the Washington system, and the Morony hydroelectric station, near Great Falls, on the Montana system. For practically all operating conditions these locations would be most representative of the hearts of the systems, and this phase-angle comparison, therefore, a better measure of stability between the two systems. It appeared to have the further advantages of (*a*) immediately recognizing an outage of any line having an appreciable effect on the interconnection capacity, such as on the parallel lines between Spokane and Burke, or between Butte and Morony; (*b*) the receiver would be located directly at the station best suited for control purposes, due to the storage capacity, large and efficient units, and short penstocks, obviating the necessity for an additional telemetering circuit or a long-distance control circuit to the control station; and (*c*) the carrier-current equipment would be located at points well suited for adequate maintenance.



A. With the predetermined limits of phase angle within a narrow range of large positive (or negative) values, resulting in operation close to the stable limit with maximum permissible power flow in one direction (or the opposite)

B. With the predetermined limits of phase angle within a narrow range between a small positive value and a small negative value, or wherever required, to result in a minimum average power flow between the systems, with maximum stability, and maximum ability of each system to help the other under emergencies

C. With the predetermined limits over a wide range between a large positive value and a large negative value, resulting in the least amount of control or definite scheduling of the amount of power flowing between systems, except as the stable limit was approached in either direction

Figure 2

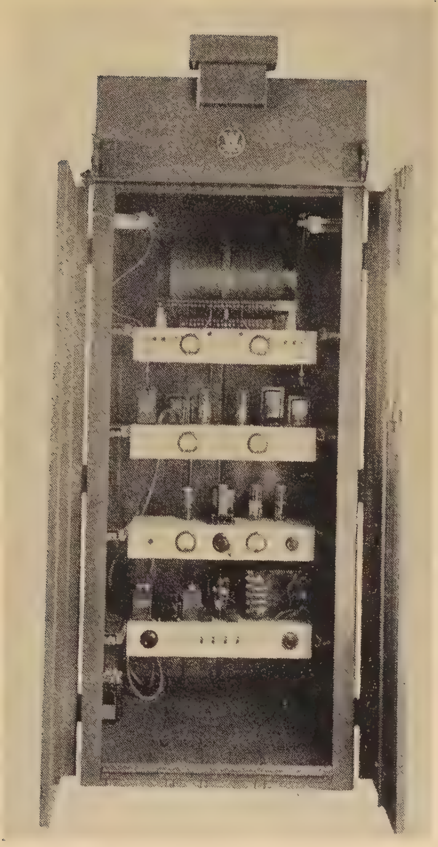


Figure 3. Carrier-current transmitter

2. Carrier-current transmitting and receiving equipment could be designed and built which would have an over-all shift or distortion, in the equipment itself, of a very small amount, probably less than five degrees, and that whatever distortion occurred would be essentially constant, and could therefore be corrected for.

3. The phase-angle shift or distortion of the signal over the entire carrier-current transmission channel might be affected by variations in temperature or weather, particularly with sleet for example; however, for long periods of time the distortion should be essentially constant and easily corrected for, and after some operating experience with the equipment, such gradual changes as occurred with changes in temperature or weather could probably be anticipated or followed fairly closely without materially affecting the degree of control.

4. One effect of outages of lines at different points in the network between the two phase-angle determination points would be to increase the net or effective impedance of the tie, and decrease the permissible power transfer between systems. In this respect automatic control based on phase angle should inherently recognize such line outages and compensate for them in correcting the interchange to values of the same relative degree of safety, with respect to stable limits.

Another effect of an outage of an intermediate line might be to change the phase-angle distortion or attentuation in the carrier-current measuring channel. As it was not planned to confine the carrier transmission to a single channel, it was believed that the loss of one of several parallel paths in the carrier channel would not seriously affect the practical operation of the control.

5. Phase-angle control equipment could readily be developed, and installed at the Morony hydroelectric station in Montana, having a generating capacity of 45,000 kw in two units, using as a basis the already-developed phase-difference recorder,* which, together with the frequency-control equipment already installed, would provide the following alternate methods of control:

*Flat Phase-Angle Control.* For controlling the phase angle to a predetermined value, or within predetermined limits, independent of frequency.

*Phase-Angle Bias Control.* For control primarily to a definite predetermined value of phase angle, but with assistance given for short periods in the control of system frequency.

*Selective-Frequency Control.* For controlling to a constant value of system frequency, but only when in so doing, the correction would also assist in controlling the phase angle to a predetermined value.

*Flat-Frequency Control.* For use as in the past, with isolated operation of the system

It was decided to proceed with the development and installation of the equipment, and the complete phase-angle control system was placed in service in December 1936.

The control equipment as installed provides for any of the four types of control described under conclusion 5, and the locations of the phase-angle determination points and control equipment were in accordance with the other conclusions outlined.

The predetermined basic phase-angle difference for control is fully adjustable to any angle (0 to 360 degrees), but the width of band around this base reference control point is adjustable up to plus or minus 30 degrees.

With reference to the three alternate methods of interconnected operation previously described in figure 2, and designated as *A*, *B*, or *C*, which were conceived as possible with this type of control, the equipment as installed, therefore, has sufficient flexibility for method *A* (maximum interchange in either direction); and method *B* (maximum stability or minimum interchange), but method *C* (minimum control or scheduling) is applicable only within the range of plus 30 degrees to minus 30 degrees.

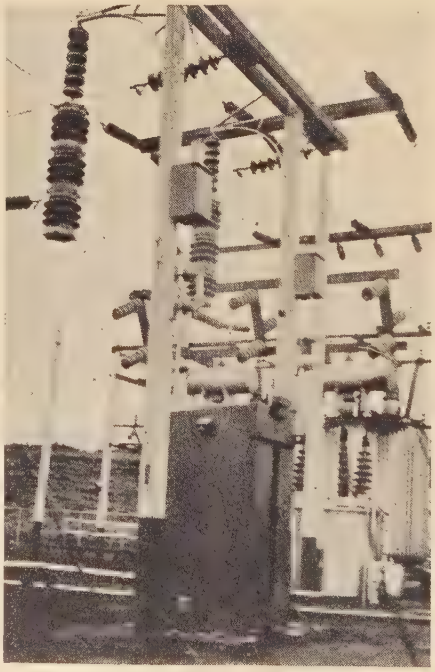


Figure 4. Transmitter installation at East Side substation, Spokane, Wash.

## Description of Carrier-Current Equipment

The carrier-current equipment was manufactured by Westinghouse Electric and Manufacturing Company and consists of:

1. A transmitter, surge protective equipment, and coupling capacitors, located at the East Side substation in Spokane, on The Washington Water Power Company system.

2. A receiver, surge protective equipment, and coupling capacitors, located at the Morony hydroelectric station, near Great Falls, on The Montana Power Company system.

The distance between the transmitter and the receiver, by transmission circuits, is approximately 460 miles. Coupling is between one phase wire and ground. No wave traps were installed at any point, so that the carrier-current signal is permitted to flow over the entire 110-kv network of the group of interconnected systems.

The carrier-current transmitter, shown in figures 3 and 4, has a frequency range of 50 to 150 kilocycles and is rated 150-watts modulated output. The oscillator is of the Colpitts type, followed by one stage of class *A* and one stage of push-pull class *B* amplification. The circuit is plate-modulated, using a single transformer, with excitation from a potential transformer connected to the East Side substation 110-kv 60-cycle bus. The outdoor steel cabinet houses the tuning inductance as well as the transmitter proper.

The carrier-current receiver, shown in figure 5 is of simple design, and consists of a detector and two stages of resistance-coupled amplification. The receiver delivers one-watt output. Two tuning controls are used, one for input and another for grid tuning. Meters are provided for indications of filament voltage, and final output plate current. The receiver is housed in an outdoor steel cabinet together with its tuning inductance. All the receiver components are mounted on one panel in this cabinet and can be readily removed.

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*"Voltage Regulation and Load Control," H. C. Forbes and H. R. Searing, AIEE TRANSACTIONS, 1934, pages 903–09.

The surge protective equipment at each location consists of a 7,500-volt Deion fuse, two enclosed gaps, and one drain coil, all equipped for outdoor mounting.

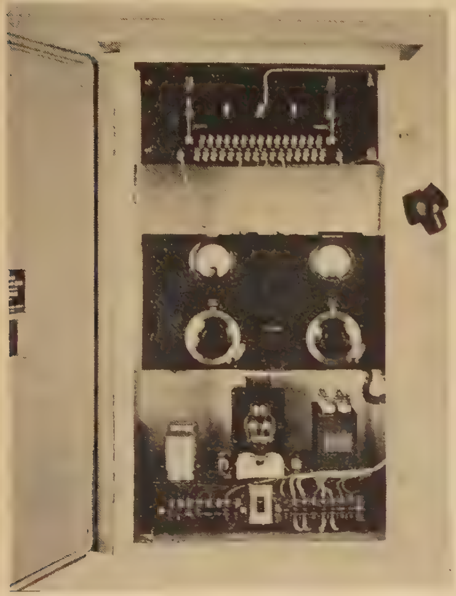


Figure 5. Carrier-current receiver

The line coupling capacitors at each location consist of three suspension-type units connected in series with an over-all capacity of 0.00133 microfarad

Since the accuracy of this equipment depends upon the constancy of the phase-angle difference between the transmitter modulating voltage and the receiver-output voltage, careful consideration was given in the design to limit this phase difference and to minimize variations thereof. The completed equipment was checked to determine the magnitude and variations in this angle, by means of a cathode-ray oscillograph, but the angle was found to be so small that it could not be accurately measured in this manner. For all practical purposes in this application, the shift in phase angle in the carrier equipment itself was considered to be of negligible magnitude.

Another feature of this equipment, while not a new engineering development nor confined exclusively to this set, is the use of iron-cored transformers for carrier frequencies of 50 to 150 kilocycles. By giving special consideration to leakage reactance and distributed winding capacities, efficiencies have been secured at 150 kilocycles that are comparable with commercial 60-cycle transformers.

## Description of Automatic-Control Equipment

The fundamental control equipment for phase-angle, frequency, and load control was manufactured by Leeds and Northrup Company; auxiliary switchboard equipment by Westinghouse Electric and Manufacturing Company. The complete control equipment as installed at Morony hydroelectric station includes the following major items:

1. Manually operated phase shifter
2. Phase-angle recorder controller with automatic-droop corrector
3. Frequency controller
4. Proportionate load controller
5. Frequency recorder

These various items perform the following functions in the complete control system.

The manually operated phase shifter is connected in the potential circuit from the Morony bus, and is used to shift this reference voltage by the number of degrees desired to be maintained between the two systems. The controller will maintain this difference by controlling to zero degrees on the phase-angle recorder-controller. Theoretically the phase shifter also may be considered available to correct or compensate for any phase-angle shift occurring in the carrier-current transmission of the remote reference voltage, but in practice this step is unnecessary and the over-all apparent phase-angle difference is used.

As its name implies, the phase-angle recorder-controller produces a graphic record of the relative phase angle of the local Morony bus voltage (as corrected by the phase shifter), with respect to the reference voltage (the received indication of the Spokane bus voltage). Deflection of the pen to the left of the center of the chart indicates Morony voltage (as corrected) lagging with respect to Spokane. In effect, therefore, this instrument gives a micrometer reading of the algebraic difference between the phase-shifter setting and the apparent phase-angle difference between the bus voltages. The recorder has a range of plus and minus 30 degrees which is more than ample to cover the normal variations from the base setting. This record on the ten-inch chart gives a very open scale and permits direct readings to one degree of phase-angle difference.

The measuring circuit of the phase-angle recorder is shown schematically in figure 6, and is basically a form of a-c potentiometer which employs the null method of measuring the angle between the two sources, shown connected to *E*1 and *E*2. If these voltages are exactly in phase, the recorder galvanometer will balance when the pen and indicating pointer are exactly in the center of the scale. If the voltage of the Morony bus, as corrected by the phase shifter, lags or leads the reference bus voltage (the received indication of the Spokane voltage), in time phase, a current will flow through the galvanometer, causing the "micromax" balancing mechanism to change the relative values of capacity and resistance in the measuring circuit until zero deflection of the galvanometer is obtained. The recording pen and the indicating pointer move as a unit with the balancing mechanism to show the new phase-angle difference.

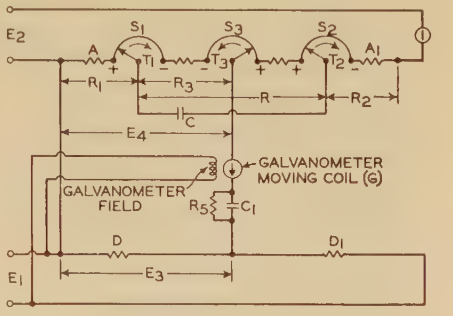


Figure 6. Measuring circuit on the phase-angle recorder-controller

Besides measuring and producing a graphic record of the phase-angle difference, this instrument contains the necessary contacts and control slidewires for originating correcting impulses which are sent to the governor motors to vary the Morony generation as required to maintain the desired phase angle. A unique feature of this control is an automatic-droop corrector which varies the rate at which the controller restores the phase-angle departures back to schedule. If the phase-angle trend is away from the control point, a proportionately larger correction is made than when the trend is toward the control point. In other words, the control action is a function of both magnitude of deviation and trend of the deviation from schedule. This prevents the tendency for the control to "hunt," or "overshoot" and was found to be an essential feature for this application.

The frequency controller is of the standard proportional-step type. When the Montana system is operating alone, this instrument is used to maintain the frequency. It is also used in connection with the phase-angle recorder to provide a bias of phase angle on the frequency for certain operating conditions.

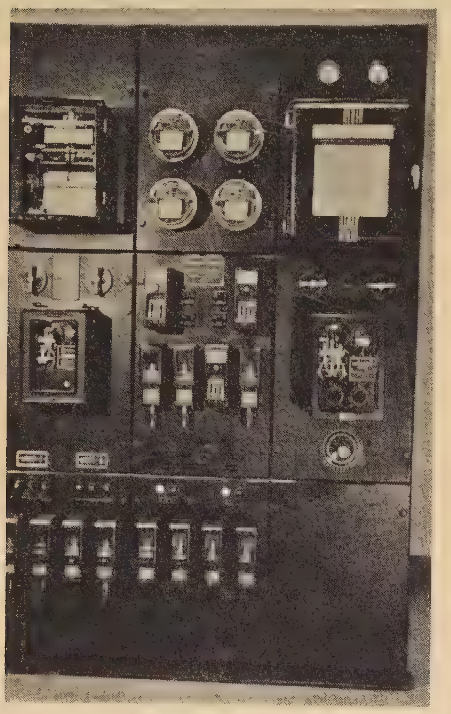


Figure 7. Switchboard control panels at Morony hydroelectric station

The proportionate-load controller is of a similar type and is used to divide the load swing with the second unit, regardless of the type of control on the station.

Contacts were added to the frequency recorder to trip the control when the system frequency departs a predetermined amount from normal, such as under fault or surge conditions.

With this equipment the following four alternate types of control, which were previously described, are available:

1. Flat phase-angle control
2. Phase-angle bias control
3. Selective-frequency control
4. Flat-frequency control

The change from one type of automatic operation to another is accomplished by a single station operation selector switch on the automatic-control panel. The appearance of this panel is shown in figure 7. Figure 8 shows the appearance in greater detail of the phase-angle recorder-controller itself.

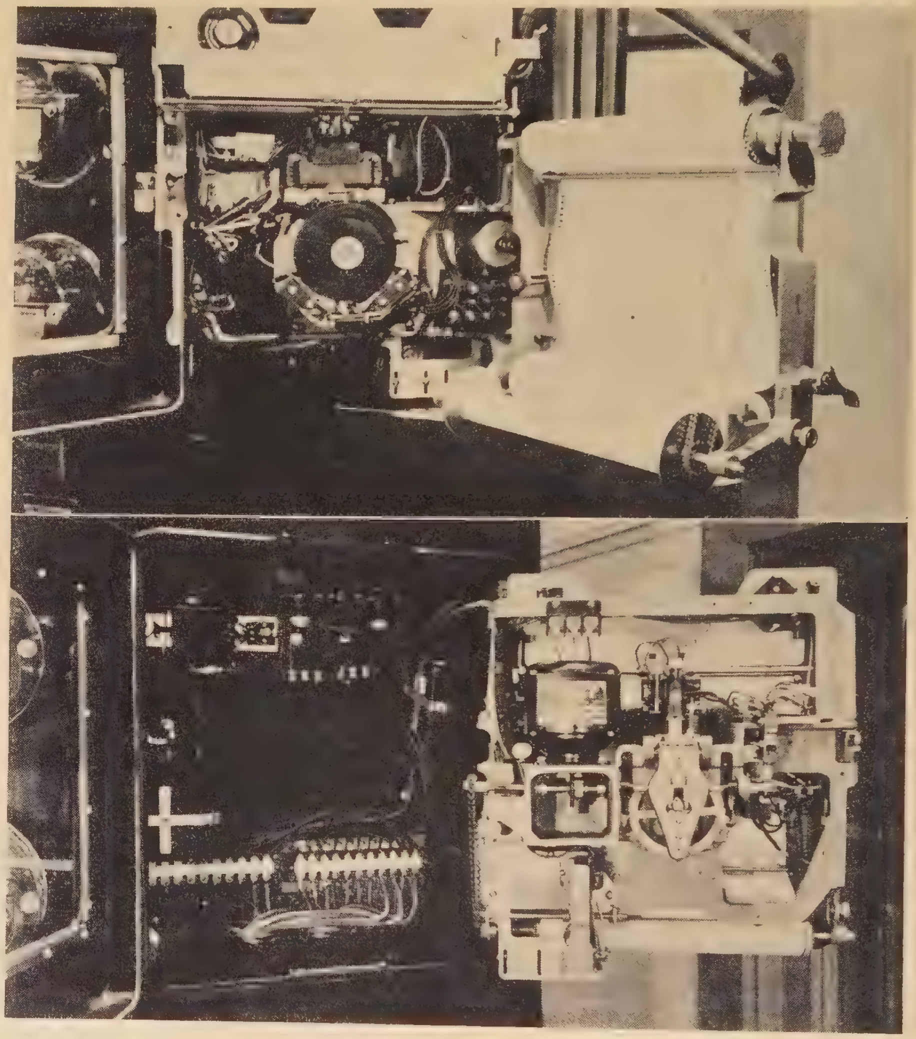


Figure 8. Views of the phase-angle recorder-controller

## Operating Experience

The complete phase-angle control equipment was first placed in service on December 10, 1936. The phase-angle recorder-controller instrument initially installed was found to have an inadequate speed of response, as the changes in phase angle occurred much more rapidly than had been anticipated. The original instrument was replaced in July 1937, with one having approximately six times the rate of control response. The operation of the control equipment has been very satisfactory and it has not required any maintenance other than oiling and cleaning.

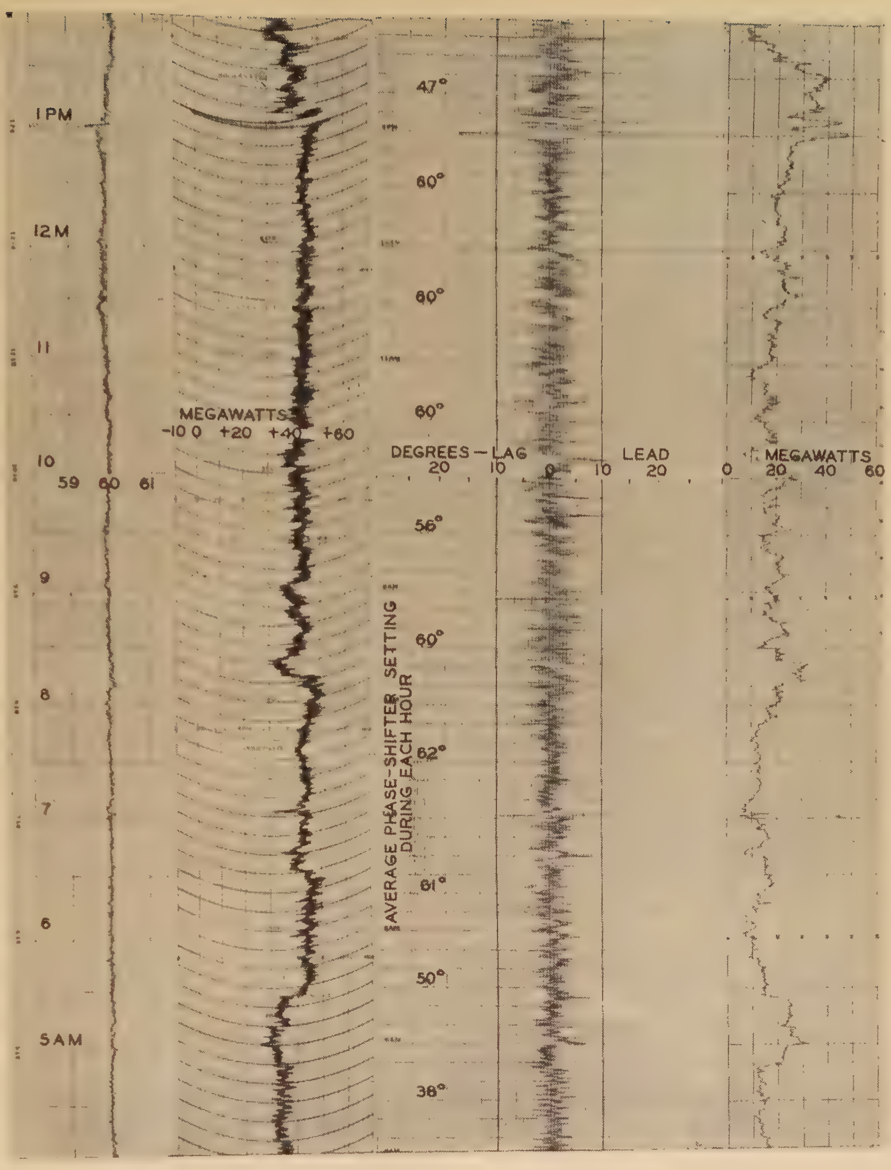
Operation of the carrier-current equipment has also been very satisfactory. The equipment was originally installed with coupling to two phases of the 110-kv system, but transmission tests indicated superior performance with coupling between one phase and ground within the frequency band desired, and operation has been on this basis. It is very seldom that a signal failure occurs due to storm conditions. While not provided in the original installation, an automatic alarm has since been added for signaling the attendant in the event of failure of the carrier-current signal. This consists of an electronic relay with the grid of the tube controlled positive by the incoming signal. On the failure of this signal, the tube stops drawing current and releases a relay, tripping off the automatic controller and operating an alarm. Maintenance of the carrier-current equipment has consisted principally of tube replacements. Both the transmitter and receiver have been modified in order to use standard tubes.

Previous a-c calculating board studies indicated that when the new line was completed, a phase angle of approximately 72 degrees between Spokane and Morony would be the "practical steady-state limit," with a corresponding total power flow eastward, consisting of the interchange at Burke plus the Thompson Falls generation, of 75,000 kw, for the particular distribution of the intermediate loads assumed. This "practical steady-state limit" was the maximum power flow or phase angle possible, consistent with maintaining the minimum allowable operating voltages at substations along the line. The theoretical steady-state power limit would be slightly higher, but was not determined in those studies. It was thought that in actual operation, the average amount of power delivered, and the phase angle to be maintained, would have to be limited to values less than the above, to allow for power swings between systems, or to approximately 65,000 kw average and 60 degrees.

Experience with the new line and the phase-angle control equipment in service has shown that when operating with an average indicated phase angle between systems of 55 degrees, the only separations of the systems are those resulting from line troubles. At 60 degrees, separations are likely to occur about once every three days (from operation of an instantaneous undervoltage relay at Burke indicating instability). At 70 degrees, operation is only possible with continuous vigilance on the part of the operators. The maximum indicated phase angle at which the systems have been operated under automatic phase-angle control, was 74 degrees, and under the system loading conditions existing at the time the total power flow eastward was 61,000 kw.

The total hourly average power flow eastward, however, has often reached 80,000 kw, the maximum recorded being 82,700 kw. For this large hourly average, the flow during the hour varied from 80,000 kw to 86,000 kw. The corresponding average phase-angle indication was approximately 55 degrees. Usually, however, an indicated phase angle of 60 degrees results in a power flow of from 50,000 kw to 60,000 kw.

Figure 9 illustrates the typical performance of the interconnection under automatic phase-angle control. In this figure, the first chart at the left is the system frequency, the second chart is a record of the power interchange at Burke (from 40,000 to 60,000 kw toward Montana), the third chart shows the variations in the phase-angle difference between systems, and the chart at the right gives the record of the Morony plant output. It may be clearly noticed that over considerable periods of time, while the average phase angle remained essentially constant, the average kilowatt interchange between systems was continually varying several thousand kilowatts with occasional changes of as much as 6,000 to 10,000 kw. This illustrates the fundamental idea of phase-angle control as contrasted to tie-line load control. Such changes in interchange indicate the normal variations in the location and magnitude of the intermediate loads on the two systems, and are to be expected and desired under this type of control. Also illustrated in figure 9, at about 1 p.m., is an instance of the systems separating unexpectedly, which is never desired. In this instance the apparent phase angle between systems reached a value of 76 degrees and the interchange at Burke 55,000 kw when the interconnection was opened by operation of overload relays.



A System frequency
B Burke interchange
C Phase-angle difference
D Morony output

**Figure 9. Typical charts showing operation of interconnection under phase-angle control**

Figure 10 illustrates in greater detail the typical comparative phase-angle variations (*a*) when the automatic controller is out of service and with the Morony output regulated manually to maintain constant phase angle, and (*b*) with the automatic phase-angle control equipment in service. Whenever the Morony output gets outside of the regulating range of the generators in service, the phase angle, of course, cannot be held at the desired value. Such an occurrence is illustrated on this chart between 8 a.m. and 9 a.m.

Usual practice so far has been to operate with "phase-angle bias control," with frequency as the major influence. It is expected that further operating experience, not only with "phase-angle bias control," with varying relative degrees of influence between frequency and phase angle, but with "flat phase-

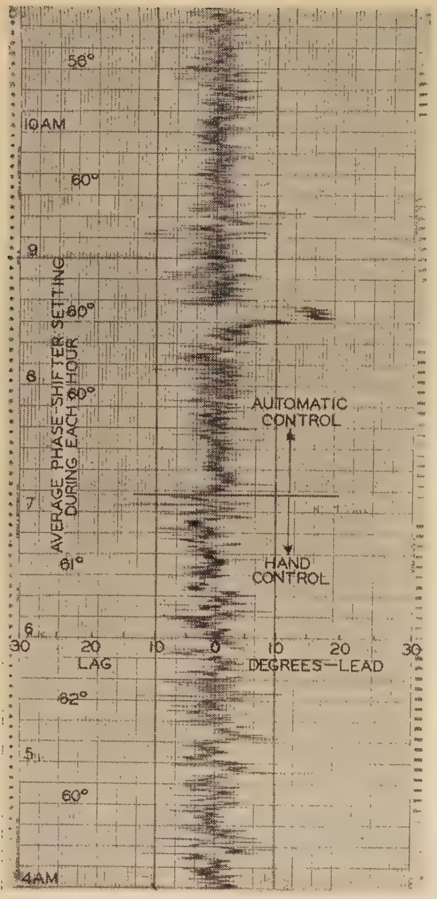
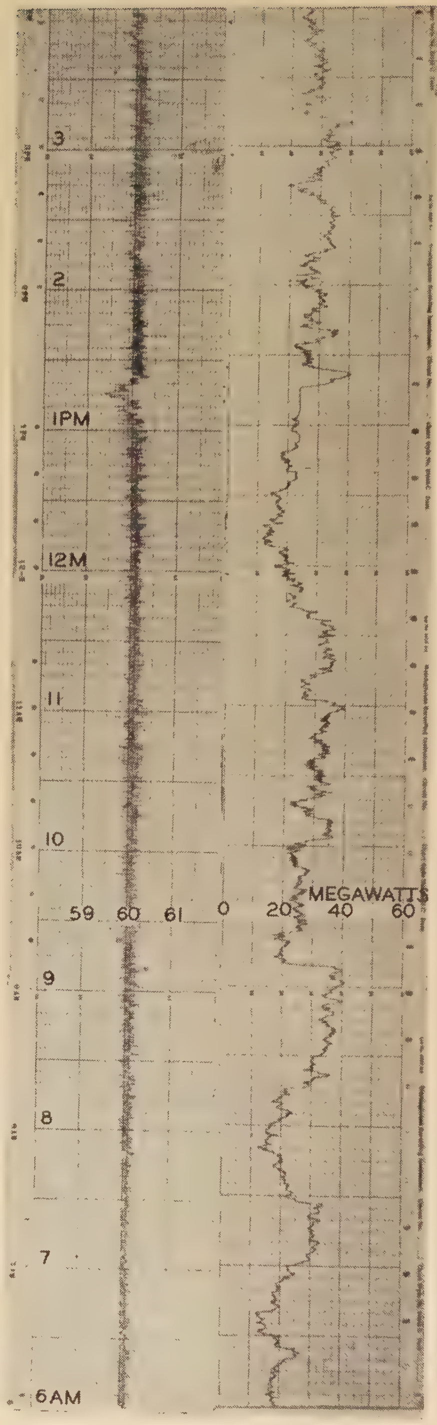


**Figure 10. Typical chart—phase-angle difference—manual and automatic control**

angle control" and "selective-frequency control," will permit more definite conclusions regarding the relative merits of different types of control for the different operating conditions that may arise.

Figure 11 shows typical charts of system frequency and Morony plant output, when the Montana system is operating isolated from the other systems, with automatic-frequency control in service at Morony. A comparison of the frequency record with that shown in figure 9 is of interest and of significance. The wider band of the frequency record in figure 11 is evidence of the relatively larger load changes with respect to the generating capacity, on the Montana system, as compared to the entire interconnected group of systems.

One of the difficult features in the control problem of this interconnection is the rapid power fluctuation as shown by the typical high-speed chart of power flow through Burke, figure 12. The governors and water wheels that are regulated by the phase-angle controller are not fast enough to eliminate these fluctuations, as tests have shown that the output of the generators does not respond to the control impulses for $4^1/_2$ to 5 seconds. While the controller helps to lessen the magnitude of the surges, it is obvious that any slow response of the governor, gate mechanism, and water column tends to lead away from the desired results. Further attempts are being made to secure faster action of the governor, thereby reducing the delay between control impulses and water-wheel response.



Montana system frequency

Morony output

**Figure 11. Typical charts illustrating isolated operation of Montana system with automatic frequency control**

A co-operative study was made to determine the cause of these rapid and persistent surges in power flow through Burke by a committee made up of representatives from each of the interconnected companies. Material for the study was obtained in a unique manner which has many possibilities for further use. It being desired to secure simultaneous readings of power flow through interconnecting ties as well as readings of power output at several stations, each company planned to install high-speed

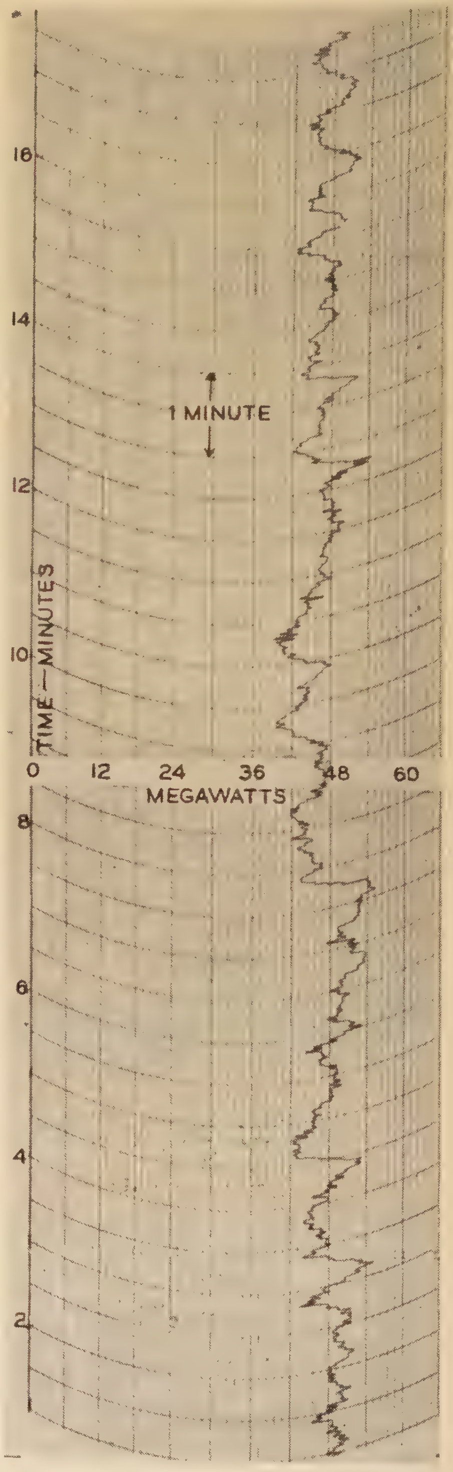


**Figure 12. High-speed chart—megawatt interchange at Burke—power into Montana**

wattmeters at key locations and one company would secure a high-speed frequency record.

In order to take numerous readings simultaneously, small homemade carrier-current receivers were installed at the location of each recording meter, with these receivers tuned to the phase-angle carrier frequency. In accordance with prearranged schedules, an observer at Spokane interrupted the carrier signal for a fraction of a second at regular intervals of 30 seconds. At each interruption the various observers marked their respective recording charts. In this manner simultaneous readings of power flow were taken on the systems of the Northwestern Electric Company, Puget Sound Power and Light Company, Pacific Power and Light Company, The Washington Water Power Company, and The Montana Power Company. As these charts indicated that five out of six times when the flow of power into Montana increased, the frequency was lower, indicating apparent power increases in Montana, and as it was not reasonable to believe that this proportion of the load changes occurred in Montana, further studies were made. It was concluded that many of the swings were not so much the direct result of actual load changes, as evidence of disproportionate and untimely increases in power input from certain systems and stations in endeavoring to restore system speed to normal—definitely indicating a lack of co-ordination of governors, both steam and hydraulic. If all governors had the same speed of response, the situation should be considerably better. This problem is still being studied co-operatively by the several companies.

## Conclusions

Installation of automatic control based on phase angle has accomplished the following:

1. Made it possible more completely to utilize the capacity of the interconnection transmission facilities, practically up to the stable limit at all times, and thereby transfer greater amounts of energy. During one month, over 30,000,000 kilowatt-hours, an average of about 45,000 kw, or 70 per cent of the stable limit, were transferred.

2. Improved the operating performance of the interconnection by permitting large transfers of power without numerous separations of the systems. The average power flow possible with satisfactory performance is in the order of 20 to 25 per cent greater than that possible with manual control.

3. Relieved the operating personnel of much of the continuous and tedious supervision of the power interchange, decreased the number of telephone calls between operators and dispatchers, and minimized the manual operation of the controlling plant.

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# Discussion

**V. M. Marquis** (American Gas and Electric Service Corporation, New York, N. Y.): The paper by Messrs. Pierce and Hamilton describes another method of approach on the problem of regulating power flow between interconnected systems and is especially applicable where there are many intervening loads, the magnitude of which are of a highly fluctuating character. As interconnected systems have grown, it has become more and more apparent that merely tying together systems does not mean interconnected system operation unless the technique of operating these interconnections is properly developed. Great strides have been made over the past few years in developing this technique and there still remains work to be done.

On most large interconnected systems it has become apparent that to regulate properly the power flow between systems and thus maintain schedules manual control alone is not in general satisfactory. Some form of automatic control is usually necessary. For the most part it has been possible to work out a combination of frequency and tie-line control by simply using an indication of the power flow on tie lines either at the point at which the regulating is done or by telemetering from the proper point on the tie line.

The problem which the authors of this paper had to meet is somewhat more difficult due to the limitations in capacity of the lines and due to the nature of the loads tapped off between the systems. The result obtained in this case is ample proof of the effectiveness of the control system described by the authors. Although this development may have rather limited application, it is gratifying to know that another tool has been developed for improving the operating technique of interconnected systems.

**A. N. Geyer** (Woodward Governor Company, Seattle, Wash.): It has been a pleasure to hear Mr. Pierce talk about this unique control arrangement, about which we have been hearing good reports at several other meetings here in the Northwest during the past year or so. It has been my privilege to study even more accurate charts representing its performance, these being high-speed charts taken like the one of figure 12 at about one inch per minute. When such charts are assembled as in figure 9, with time markings all coinciding, the record of the phase angle is seen to follow very closely the changes of power in the tie line. Likewise, a further comparison of the Morony output curve shows very definitely the extent to which these are in agreement or conflict.

For example, take a conspicuous increase in power flow toward Montana, and straight below we look for an upswing of Morony output, with whatever delay actually occurs. Since this is given in the paper as being often four or five seconds, it seems unfortunate that the telemetered indication of upswing, after being transmitted immediately for several hundred miles to the generating station, is there delayed like this in going the remaining few feet to get the needed response on the prime mover.

Regarding the later reference to the unco-ordinated action of various governors on the interconnected systems, this would seem very likely when remembering that a good many of these are early-day models, thus not representing a high-grade performance on a par with this other part of the equipment concerned in this new method of control. A direct showing of how such old governors often perform may be seen in those particular plants where the several units are in a line enabling an observer at one end and looking across them to see the relative movements, and as the speed changes in regular manner, the governor movements are seen not to be together, but even traveling in opposite directions at times, indicating that they can't all be right. From what I have observed I feel this is an explanation of earlier reported hunting swings across this Northwest interconnection that was observed to occur a few times a minute in a plain showing on the charts. But the case is different with modern precision governors, contrary to the commonly expressed fear of "governors fighting each other," for if all are very sensitive to start early in any speed change, and are stabilized to stop where needed through proper dashpot action insured by correct field adjustments, they don't do the wrong thing any more than does some other highly developed precision apparatus. Then with all working correctly in response to any change in speed, their benefits are cumulative in maintaining close speed.

To bear out these statements by referring to a situation of interconnection and power regulation that is a very close parallel to the problem under discussion, I want to say that during the past year I have been working on improvements on governors where a rough mining load at one end near a group of hydro plants is connected over the mountains with a larger system which has a regular lighting and commercial load but uses an automatic frequency controller. The situation was just the same as here, in that the tie-line loading must not be allowed to go high enough to cause difficulty. Hence in order to prevent the heavy mining load fluctuations from flowing through the interconnection, these changes must be absorbed largely on their own system, that is, by their own hydro units. Now this must be done in spite of the average frequency controller on the other system. This called for the highest order of sensitivity in these governors, also the fastest rate of operation practicable. By modernizing these governors, they were put into the class of good modern governors and by using the very smallest droop practicable, they were enabled to respond well to every quick change of speed to take most of the load changes on their own system. In order to help hold the steady-state loading desired in the tie line, a telemetering arrangement was put in to indicate in the controlling station the power flow in the interconnection. This is valuable to the operator in avoiding slow drifts at any time including those during the beginning and end of working shifts at the mines.

In order to assist in this holding of the average loading in the tie line, it is the plan to go farther and make the whole thing automatic, by arranging to put this tie-line loading influence directly on the governors. This is being done, however, in a manner considerably different from the usual practice of using the synchronizing motor, by making the action direct on the governor controls. It is hoped that more operating results of this whole equipment may be reported later.

**Sherwin H. Wright** (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): In system planning and design it is usually transient stability, rather than steady-state stability that receives first consideration. This is logical, for steady-state stability limits are usually much higher and less important than the transient stability limits. Attention has therefore been focused for some time on methods of increasing transient stability limits, resulting in such developments as high-speed breakers and relays, quick-response excitation, and most recently, high-speed reclosing breakers.

During this development period system interconnections have become the rule rather than the exception and while transient stability of such interconnections is still lower than steady-state limits, yet the latter are for various reasons quite important, as in the case described in this paper by Pierce and Hamilton. The authors describe a case involving several large-size systems as evidenced by the capacities given in the article:

| | Kilowatts |
|---|---|
| The Montana Power Company | 250,000 |
| The Washington Water Power Company | 200,000 |
| Puget Sound Power and Light Company | 300,000 |
| Pacific Power and Light Company and Northwestern Electric Company | 120,000 |
| Portland General Electric Company | 175,000 |
| Washington Gas and Electric Company | 30,000 |

Thus it is seen that the total generating capacity involved is considerable, and it is quite probable that there are similar system groups in existence where phase-angle control apparatus can be and will be successfully applied.

It is pertinent to note that this phase-angle control equipment, since it controls the phase angle, is applicable in situations where phase-angle difference is a suitable and preferable control index. In the application described by the authors it was recognized (1) that the highest limit is the steady-state stability limit, (2) that the steady-state voltage limit is somewhat lower, and (3) that the control should be set for a value lower than (2) in order to allow margin for continual power swings between the systems.

As stated by the authors, the reason that kilowatt loading in itself is not a proper index is because along the interconnection there are loads which vary in both location and magnitude; such a situation gives phase-angle the preference over kilowatt loading as a control index. Under such conditions of variable location and magnitude of intermediate loads, phase-angle control may find successful application in not only cases where steady-state stability or steady-state voltage determines the practical operating limit, but also in cases where the practical limit is determined by transient stability for faults on the interconnection itself.

**H. L. Melvin** (Ebasco Services, Inc., New York, N. Y.): This discussion of the paper by Messrs. Pierce and Hamilton is presented for the purpose of amplifying somewhat the section dealing with operating experience. Because of the familiarity of the discusser with the interconnected operation of the Pacific Northwest systems during the past several years, the liberty is being taken of relating two or three items of interest which might more properly be presented by representatives of the several utility companies.

The paper gives a brief report of the high-speed chart-marking tests at interconnection points and controlling power stations. It was suspicioned that variations in governor sensitivity and dead time between the closing of governor-motor contacts and the kilowatt response of the generators were responsible to a large degree for the occasional large power swings and to some extent the amplitude of the regularly occurring swings. To check this suspicion, a photoelectric frequency recorder with an auxiliary mechanical pen was borrowed from the General Electric Company and preliminary tests were made to determine the characteristics of several governors on the interconnected systems. These tests demonstrated conclusively that unco-ordinated governor and automatic phase-angle control action could be accountable for the magnitude of at least a part of the power swings. The tests were not complete nor was the frequency recorder alone adequate for the purpose. Accordingly, the Washington Water Power Company purchased and has just received a General Electric, two-element, photoelectric recorder which will make a record of frequency and kilowatts; also, it has two auxiliary pens for mechanical attachment, all on one variable high-speed chart. It is planned to use this instrument for analyzing, adjusting, and co-ordinating the operation of governors, also automatic tie-line load-control equipment on the interconnected systems. The recording and analyzing of power flow at interconnection points with variations in system frequency also can be accomplished.

Since the paper was prepared, there has been placed in service an automatic tie-line load-control equipment of General Electric Company manufacture between the systems of the Puget Sound Power and Light and The Washington Water Power companies. Kilowatts interchange on the Chelan-Wenatchee interconnection is transmitted by carrier signals to the White River plant on the Puget Sound Company's system and the output of this plant is automatically controlled to hold the interchange at desired values. It, like the automatic phase-angle equipment between Washington and Montana, is working successfully.

Though all of the systems from Montana to the Pacific Coast are now operated successfully in parallel, it is expected that improvements will be realized through further application of automatic load-control equipment and better co-ordination of governor and automatic control action after completion of tests with the photoelectric frequency and kilowatt meter. Progress will be made only if this work is carried on in the splendid co-operative spirit which exists among the operating organizations; also between the electrical, hydraulic, and mechanical engineers involved.

It should be remembered that the capacities of the interconnections are rather limited and distances in the Northwest are relatively great. However, with maximum utilization of the interconnection facilities it is believed that present capacities will be adequate for some time. Economics and service are controlling considerations rather than the control of interchange to precise demand values, which in reality should have little if any place in interchange agreements.

**R. E. Pierce** and **B. W. Hamilton:** The authors are gratified at the interest shown in the new method of control described. We concur in the view of the several discussers, and would like to emphasize some of these points.

Mr. Geyer brought out very well that the apparent lack of co-ordination between the various governors and with the automatic control equipment would perhaps not exist were the governors of modern and sensitive design and properly adjusted. We also anticipate that somewhat improved co-ordination and over-all system performance can be obtained, even with the present installed governors, following completion of the further studies mentioned and following whatever maintenance and adjustments that may be indicated as necessary. This will probably include making certain governors less sensitive for small speed variations (and considerable more thought being given to speed-droop setting). Mr. Geyer also describes a somewhat parallel case, where it is planned that automatic control of an interconnection will result in practically all of the load swings on one system being absorbed on that system. The results secured will be of interest, and we hope will be reported.

As Mr. Marquis points out, some form of automatic control is usually necessary to maintain scheduled power flows between systems, but that in the situation described, we were attempting to do somewhat more than maintain a scheduled flow. Inasmuch as any predetermined scheduling of power flow at some arbitrarily selected interconnection point (usually wherever ownership of facilities changes) does not always result in maximum utilization of the transmission facilities, it is pertinent, as Mr. Melvin has done, to raise the question as to whether definite scheduling of interchange flows to precise demand values is always the best over-all practice. In our opinion, there are probably many interconnections where the full capabilities of

# Static Power Limits of Synchronous Machines

By CHARLES F. DALZIEL
ASSOCIATE AIEE

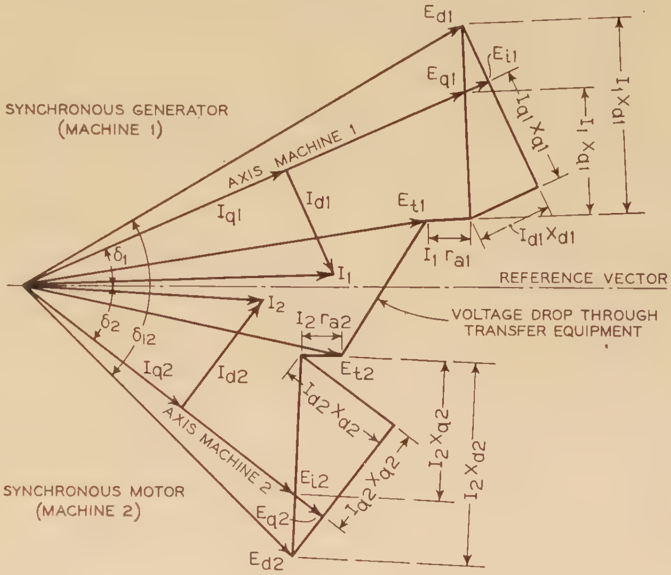
THIS paper presents an analysis of the determination of static power limits of power systems and offers an accurate method considering resistance, shunt loads, saliency, and saturation. The conventional methods of determining the static power limits of systems composed of synchronous machines and shunt loads based on unsaturated cylindrical-rotor theory give only approximate results. It is fortunate that the actual maximum power transfer is generally larger than the calculated value obtained from the customary analysis. Machine saturation and saliency increase the power limit, the difference decreasing with increased system impedance. The validity of the method is shown by the check between experimental values obtained from three small machines and theoretical curves. It was found that errors due to neglecting saturation are more significant than those due to neglecting saliency.

Static power limits are important because they may be exceeded under emergency conditions, even though the system is designed to operate well below these limits normally. Although transient stability will probably continue to be regarded the most important factor limiting the power transfer through most practical systems, recent accomplishments which increase the transient limit reduce the difference between the transient and static power limits, and an accurate analysis of static power limits is of increasing importance. It is possible that studies made on operating systems might indicate minor or preferred changes in load dispatching which would result in higher power limits and greater margins of stability, ultimately reflecting increased reliability of system operation.

Much data included in this paper were obtained by graduate and senior students under the writer's supervision. No serious experimental difficulties were encountered, and a number of the runs were repeated and rechecked at various times during the past three years.

It has been shown that inertia effects may cause a difference between the maximum power output and the static stability limit.[1] In the experimental work reported here, the difference between the maximum power and static stability limits was negligible for synchronous generator-motor systems. Systems involving two generators and shunt loads were much more stable, and it was possible to operate the machines with displacement angles up to 91 electrical degrees. However, when the displacement angles exceeded that corresponding to maximum power output, the machines were in unstable equilibrium and required very careful supervision, any slight misadjustments causing immediate loss of synchronism. It was concluded that for practical purposes static stability may be regarded as a problem of stable equilibrium in which all transient phenomena and inertia effects are neglected.[2] This is in agreement with the recent report of the AIEE committee on the subject.[3]

**Figure 1. Vector diagram — synchronous generator-motor system**



The stability limit is determined by the first synchronous machine to reach its maximum power output. A system is considered stable if all the machines are operating in stable equilibrium. It will be unstable if any machine is unstable.[2] A machine operates in stable equilibrium if each additional increment of load is accompanied with a corresponding increasing increment of displacement angle. For each machine a critical load will finally be reached which is the maximum load the machine can carry and operate in stable equilibrium with respect to the other machines. If further attempt be made to load the

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1. For all numbered references, see list at end of paper.

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the facilities should be utilized, and efforts made to equitably share the burdens and benefits between the interconnecting parties, rather than to make extraordinary efforts to control the operation to maintain arbitrarily predetermined interchange values.

We agree with the opinion expressed by Mr. Wright that phase-angle control may find application where the practical limit is determined by transient stability, a well as in cases, such as the one described by the authors, where it was desired to operate beyond the transient stability limit and as close as practicable to the steady-state limit. In either case, the phase-angle difference between systems is the basic determining factor between stable and unstable conditions.

machine, it will be found that increasing increments of displacement angle are accompanied by decreasing increments of load, and the machine will be unstable equilibrium.

Static stability refers to the normal power transfer through a system, and should not be confused with transient stability in which the effects of disturbances are considered. Two static power limits are distinguished:

I. The steady-state power limit is defined as the maximum power that may be transferred through a network without loss of synchronism when the machine excitations are maintained constant at the values necessary to produce the terminal voltages required for the initial system loading. It is assumed that the disturbance caused by the addition of each increment of load has ceased before the next increment is applied.[4]

II. The dynamic power limit is defined as the maximum power that may be transferred through a network without loss of synchronism when the machine excitations are varied either manually or by automatic devices to maintain the voltages at one or more points at constant, or at definite values. It is assumed that the disturbance caused by the addition of an increment of load is over before the next is added, and that the increments are applied at a slow enough rate to permit the restoration of the system voltages before the next increment is added.

The power-angle equations for a system involving $n$ salient-pole machines have been taken from Longley.[5] The general case is complicated due to the number of variables involved. Fortunately, the important two-machine problem can be solved easily and derivations of power and current-angle equations are given in the appendices. The author believes this is the first time concise equations for two salient-pole machines have been published.[6]

## Determination of the Steady-State Power Limit

The machine internal voltages are determined from the known or assumed load and substituted in equations 11 and 12 (see figure 1). The displacement angle ($\delta$) is arbitrarily increased and the first machine to reach its maximum power output determines the power limit of the system. The steady-state limit is of minor interest in power systems, but it is important in determining the pull-out torque in synchronous machines using fixed excitation or manual control.

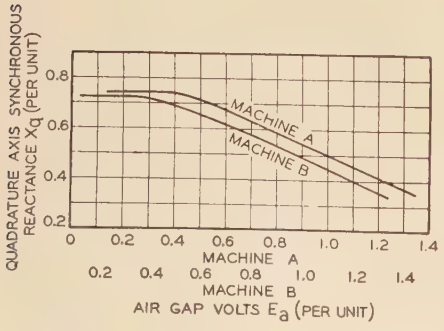

**Figure 2. Variation of quadrature-axis synchronous reactance with air-gap voltage**

## Determination of the Dynamic Power Limit

The dynamic power-angle curve intersects each of a family of steady-state power-angle curves at points of known voltage and current. The limit of stable equilibrium of a synchronous machine occurs when the dynamic curve intersects the first steady-state curve at its maximum point. This point may be determined by plotting stability coefficients for increasing values of power or displacement angle. The first stability coefficient to change sign determines the power limit. Since the voltages and currents are known, equations 13 and 14 are used to determine the stability coefficients. For this case the system impedances contain $X_q$ of the machines, and $E_d$ represents the voltage behind the quadrature synchronous reactance.

Although not stated in the paper by Edith Clarke and Lorraine,[2] their analysis may be used to determine the dynamic power limit of systems composed of three or more salient-pole machines if their equations 1 to 8 contain the $X_q$ of the machines and the corresponding voltages behind $X_q$.

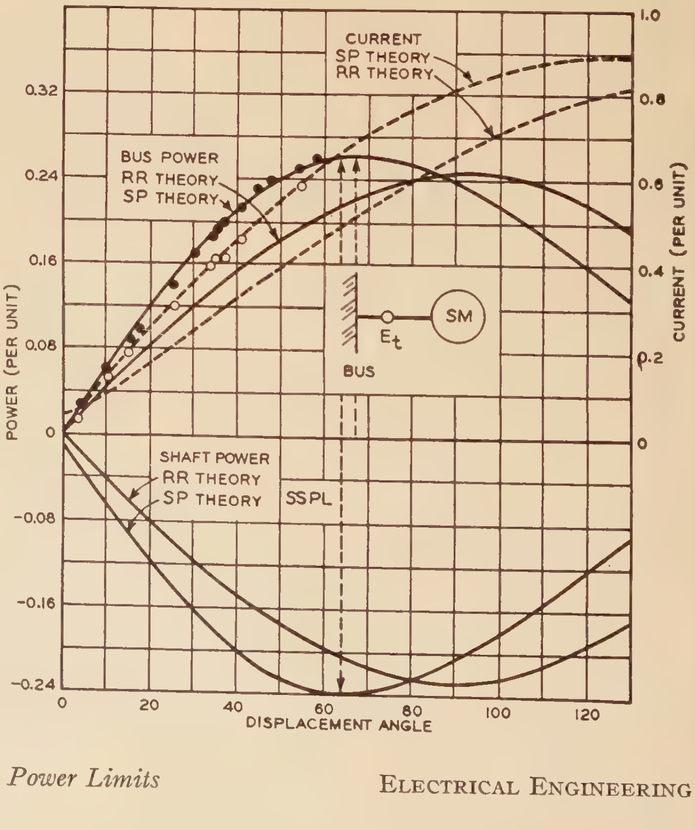

**Figure 3. Unsaturated synchronous motor operating from an infinite bus**

*SP*—Salient pole

*RR*—Round rotor

*SM*—Synchronous motor

*SSPL*—Steady-state power limit

For cases in which the system voltages are maintained constant, all shunt loads including synchronous condensers and induction motors may be represented approximately by simple shunt impedances. This treatment assumes that the induction motor portion of the system load remains stable. Since the maximum power transfer is ordinarily limited by the synchronous machines on the system, this assumption should not introduce significant errors in the result. See references 2 and 7 for accurate treatment.

## Consideration of Saturation

Saturation in the synchronous machines was neglected in the preceding discussion. The power or current equations give accurate results if saturated values of the machine $X_q$ corresponding to the machine air gap voltages are used.[6,8] Determination of the steady-state power limit is complicated by variations of $X_q$ and the correction for saturation with current. Fortunately, the dynamic limit, which is the most important from a practical standpoint, may be determined easily, since the voltages are known and the current or power is the independent variable. The saturated $X_q$ corresponding to the air-gap voltage is obtained and $E_q$ determined. These values are then used to determine the stability coefficients using equations

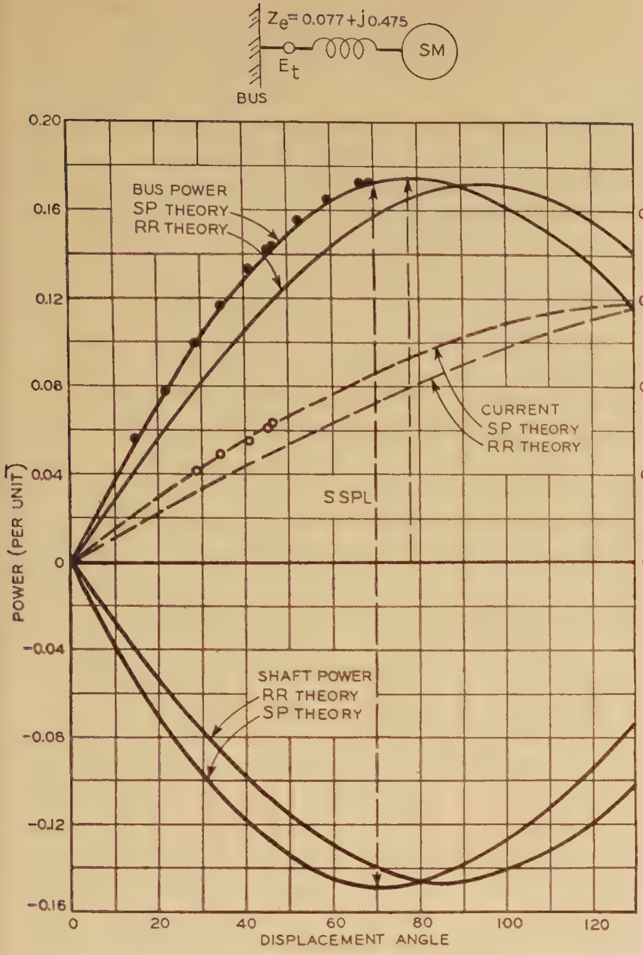

Figure 4. Unsaturated synchronous motor operating from an infinite bus, with series impedance

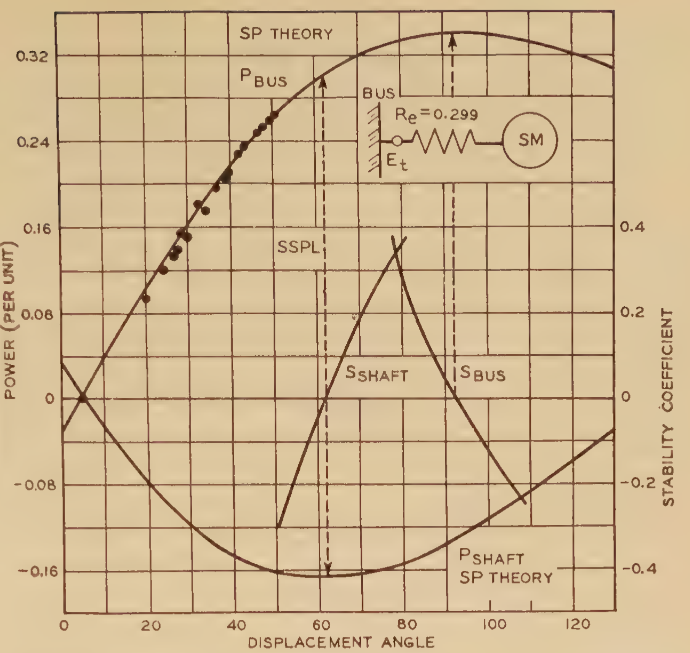

Figure 5. Unsaturated synchronous motor operating from an infinite bus, with series resistance

13 and 14. In this case the system impedances, $Z_{11}$, $Z_{22}$, and $Z_{12}$ contain the machine $X_{qs}$, and the $E_{ds}$ are the corresponding voltages behind the $X_{qs}$.

It is believed that the dynamic power limit may be approached in large power systems, since variations in load generally occur at a slow enough rate to permit modern voltage regulators and governors to maintain the system voltage and frequency. The method permits an accurate determination including resistance, saliency, and saturation. It should be of particular value in determining the maximum power transfer over single-circuit tie lines, as well as the emergency power limits of transmission systems in general.

## Experimental Results

The laboratory work centered about two similar synchronous machines rated: 15 kva, 220 volts, 39.4 amperes, 1,200 rpm, 60 cycle, 3 phase. The quadrature axis synchronous reactances versus air-gap voltage are given in figure 2.*

The unsaturated machine constants are:

Machine A. $R_a = 0.044$, $X_l = 0.072$, $X_d = 1.15$, $X_q = 0.742$.

Machine B. $R_a = 0.045$, $X_l = 0.071$, $X_d = 1.10$, $X_q = 0.722$.

## Steady-State Power and Current Characteristics, Unsaturated Synchronous Motor

Figures 3, 4, and 5 show calculated and test results of machine *A*, energized from an infinite bus at half voltage. With the excitation held constant, values of power and current were obtained for various loads up to pull-out. Theoretical power and current-angle curves using both round-rotor and salient-pole analyses were plotted to compare results. Although the round-rotor theory yields poor results with respect to displacement angle, the differences at pull-out were small, and the errors decreased with increased system impedance. The difference between the shaft and bus power was due to the $I^2R$ loss in the machine and series impedance. Motor power was plotted negative to avoid confusion.

It was concluded that the common method of determining the *unsaturated* power limits should give results of sufficient accuracy for most engineering purposes. It will be shown that the effects of saturation are likely to cause much greater errors than those caused by neglecting saliency.

## Steady-State Power Angle Curves, Synchronous Generator-Motor System

Figures 6 and 7 show calculated and test results with machine *B* driving machine *A*. With the excitations held constant, corresponding to approximately half voltage at no load, values of power were obtained for various loads up to pull-out. Again the agreement between test and calculated results substantiates the analysis and should lead to a better understanding of the unsaturated synchronous machine.

Figure 8 shows similar results under saturated conditions. For the steady-state test, the machine excitations were held constant corresponding to rated voltage at no load. The power-angle curve was obtained as before. Calculated power-angle curves using unsaturated machine constants are included for comparison and indicate the necessity for considering saliency and saturation if accurate results are required. It is obvious that this statement applies to both steady-state and dynamic power limits. It was concluded that errors due to neglecting saturation are more

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* Per unit quantities are used throughout this discussion. 1.00 per unit power equals 15 kw.

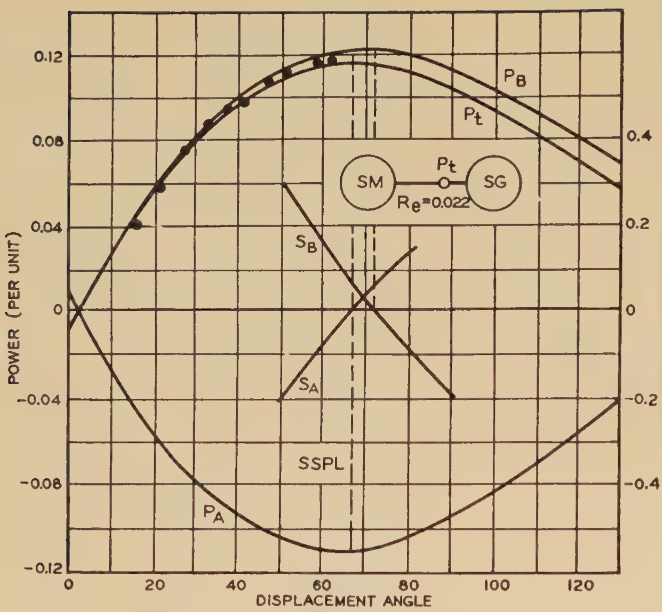


**Figure 6. Unsaturated synchronous generator-motor system**

*SG* — Synchronous generator

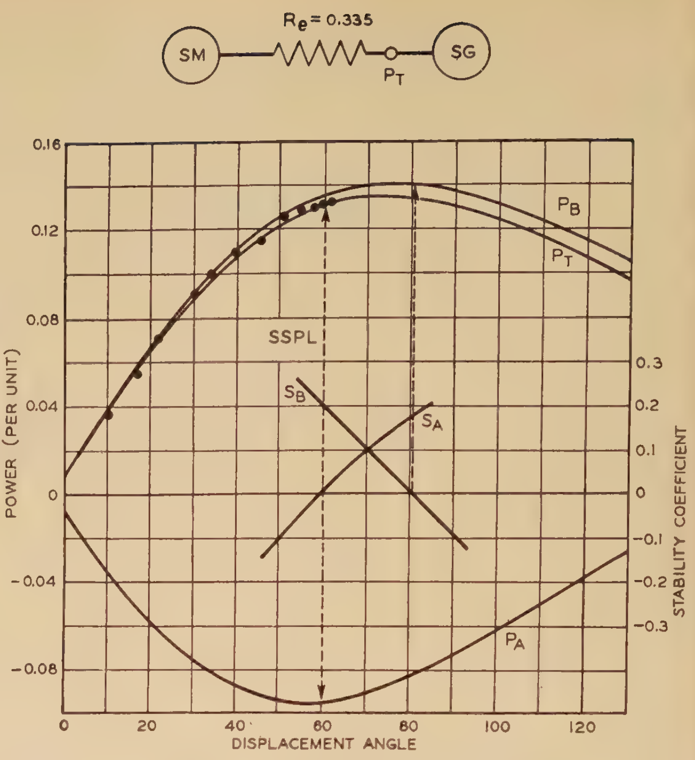


**Figure 7. Unsaturated synchronous generator-motor system, with series resistance**

significant than those due to neglecting saliency.

For the dynamic stability test, the machine excitations were varied to hold the motor terminal voltage and power factor constant at unity. The dynamic limit of the system was not reached due to limitations of equipment. The correlation between observed and calculated values for this highly saturated case is an indication of how accurately saturation may be included, since $E_2$ was held constant at rated value and $E_1$ varied from 1.00 to about 1.25.

## Two Synchronous Generators, Variable Shunt Load, and Series Impedance

In this test an attempt was made to duplicate the general two-machine problem. A variable three-phase balanced resistance load connected to the terminals of generator *A* was energized from both generators. The power supplied at the load was held in the ratio $P_1/P_2 = 2/1$, and the frequency was held at 60 cycles. Starting at no load, the delivered power-angle curves were obtained by gradually increasing the shunt load.

For the steady-state test the machine excitations were held constant corresponding to a no-load voltage, $E_2 = 0.4515$. The load was applied and the power-angle curve obtained. It is interesting to note that the two generators were inherently more stable than during the generator-motor tests and several points were obtained in the region of unstable equilibrium (see figure 9).

For the dynamic test, the machine excitations were varied to hold the load voltage constant ($E_2 = 0.4515$), and the power factors unity at the load. The method of calculating the dynamic curve will be illustrated by a specific example.

Let $P = 0.50$, $P_1 = 0.333$, and $P_2 = 0.167$

$$I = P/E = 1.108\underline{/0},$$

$$I_1 = 0.738\underline{/0} \text{ and } I_2 = 0.370\underline{/0}$$

The series impedance, $Z_e = 0.123 + j0.692$
$= 0.702\underline{/79.9}$

$$\begin{aligned}
E_1 &= E_2 + I_1Z_e \\
&= 0.4515\underline{/0} + 0.738\underline{/0} \times 0.702\underline{/79.9} \\
&= 0.744\underline{/43.2}
\end{aligned}$$

$$\begin{aligned}
E_{a1} &= E_1 + I_1Z_{l1} \\
&= 0.744\underline{/43.2} + 0.738\underline{/0}(0.045 + j0.071) \\
&= 0.804 \\
X_{q1} &= j0.571 \text{ from figure 2} \\
E_{q1} &= E_1 + I_1Z_{q1} \\
&= 0.744\underline{/43.2} + \\
&\quad 0.738\underline{/0}\,(0.045 + j0.571) \\
&= 1.096\underline{/58.2}
\end{aligned}$$

By a similar process, $X_{q2} = j0.723$ and $E_{q2} = 0.538\underline{/29.7}$

$$\begin{aligned}
\delta_{12} &= 58.2 - 29.7 = 28.5 \\
z_1 &= (0.045 + 0.123) + j(0.571 + 0.692) \\
&= 1.272\underline{/82.4} \\
z_2 &= (0.044 + j0.723) = 0.724\underline{/86.5} \\
z_3 &= E_2/I = \frac{0.4515\underline{/0}}{1.108\underline{/0}} = 0.407\underline{/0} \\
z_{12} &= z_1 + z_2 + z_1z_2/z_3 = 3.14\underline{/129.6} \\
\alpha_{12} &= -39.6 \\
S_1 &= \cos(28.5 + 39.6) \\
&= 0.373 \text{ from equation 13} \\
S_2 &= \cos(28.5 - 39.6) \\
&= 0.981 \text{ from equation 14}
\end{aligned}$$

The complete curve was obtained by repeating the process using increasing values of power. It was noted that this operating condition required large increases in $E_1$, and $X_{q1}$ varied from 0.700 to 0.468 due to saturation. Unfortunately the dynamic stability limit was not reached due to limitations of the equipment.

The dash-line curves of figure 10 illustrate the determination of the dynamic limit when the machine excitations were varied to hold both generator terminal voltages equal at 0.4515. The stability coefficient $S_{1a}$ indicates a theoretical maximum delivered load of 0.280 per unit. Although it was possible to supply a slightly greater load, the system became very unstable and soon lost synchronism.

The solid-line curves of figure 10 illustrate the determination of the dynamic limit when a 7.5-kva 220-volt 19.7-ampere cylindrical-rotor machine used as a synchronous condenser was connected at the load to maintain voltages. During this test the power supplied to the load was held in the ratio $P_1/P_2 = 2/1$, and machine *A* was held at unity power factor. The losses of the condenser were considered as part of the load. Stability coefficient $S_{1b}$ determines the stability limit of the system with a delivered power equal to 0.270 per unit.

The assumption that a synchronous condenser can be replaced with a static condenser for dynamic analysis is verified from inspection of the curve. Experimental points using three different static condensers are in good agreement with the other results.

Calculated curves showing various factors which may limit the power transfer for this typical system are given in figure 11, in which the ratio $P_1/P_2$ has been varied over a wide range. The assumed operating conditions were the same as those of the preceding test. The rapid increase in dynamic stability occurs when the machines are operating with nearly constant displacement angles between them, a condition similar to the dynamic curve of figure 9. A similar study applied to practical systems might indicate that large increases in the maximum power would be realized by minor redistribution of the system generating capacity. Curves of this type should be of interest in determining the conditions for optimum power transfer and suggest the extreme conditions to be considered in transient stability studies.

## Practical Application

The power limits of several actual systems were determined to illustrate the possibilities in the way of practical application. Although the actual power limits were unknown, available operating experience was consistent with the conclusions reached. The reactances of most of the machines were not available and typical unsaturated values were used.[3,9,10] These were multiplied by 0.90 to give a conservative correction for saturation.[11]

### San Diego Consolidated Gas and Electric-Southern California Edison Interconnection

In the summer of 1932, the small 50/60-cycle frequency converter interconnection of the San Diego Consolidated Gas and Electric-Southern California Edison Company was operated for a considerable period in utilizing "spillway" from the Edison system. During certain times of the day when the system loads were changing most, it was a common experience for the converter load to increase to some value slightly in excess of 7,500 kw, and its breakers would trip on out-of-step operation. The converter excitation system included one automatic voltage regulator which could be connected to either side of the machine. It was found possible to choose the system on which instability would develop, and best results were obtained with the regulator connected on the 60-cycle system. It was desired to hold the average converter load at about 5,000 kw.

In calculating the dynamic power limit it was assumed that all terminal voltages were maintained constant at rated values and that the San Diego system loads remained constant at the average values given in figure 12. It was concluded that the 60-cycle side of the converter should control the dynamic stability of the system and permit a maximum load transfer of approximately 16,400 kw (see figure 13). The steady-state power limit of the 50-cycle system was determined at approximately 8,000 kw assuming constant converter excitation corresponding to an initial load transfer of 5,000 kw. The result compares favorably with operating experience and stresses the value of automatic excitation equipment. It is the writer's opinion that the higher power limit could have been approached and the operating difficulties reduced had modern excitation equipment been provided.

### Hetch Hetchy-Pacific Gas and Electric System

The City of San Francisco's Hetch Hetchy system is an example of a large hydroelectric project feeding power over a long transmission line into an infinite bus (see figure 14). Since the lines were originally designed for 154 kv, but were insulated and operate at approximately 110 kv, and the operating orders limit the power transmitted over one line to 40,000 kw, it was thought that a study of the maximum or emergency power limits might be valuable as well as instructive. The dynamic power limit was determined at approximately 92,500 kw for normal operating voltages and

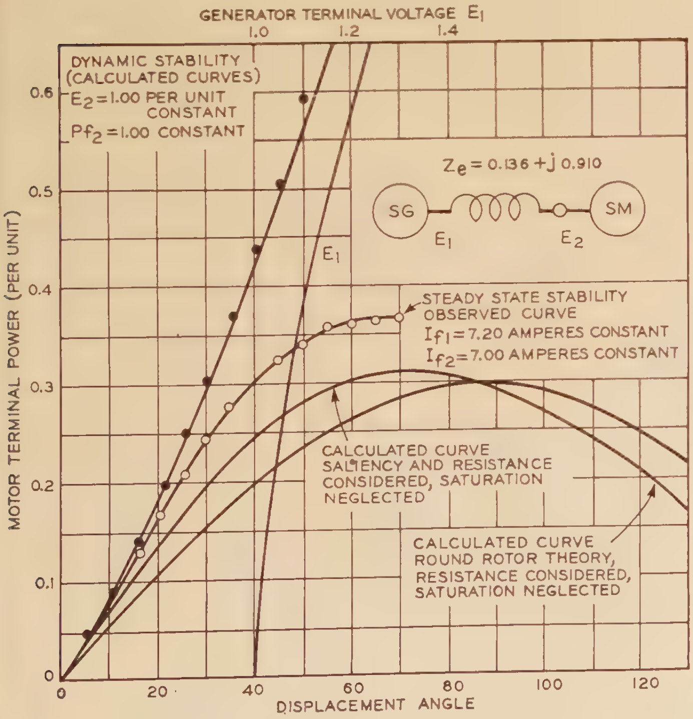


**Figure 8. Saturated synchronous generator-motor system with series impedance**

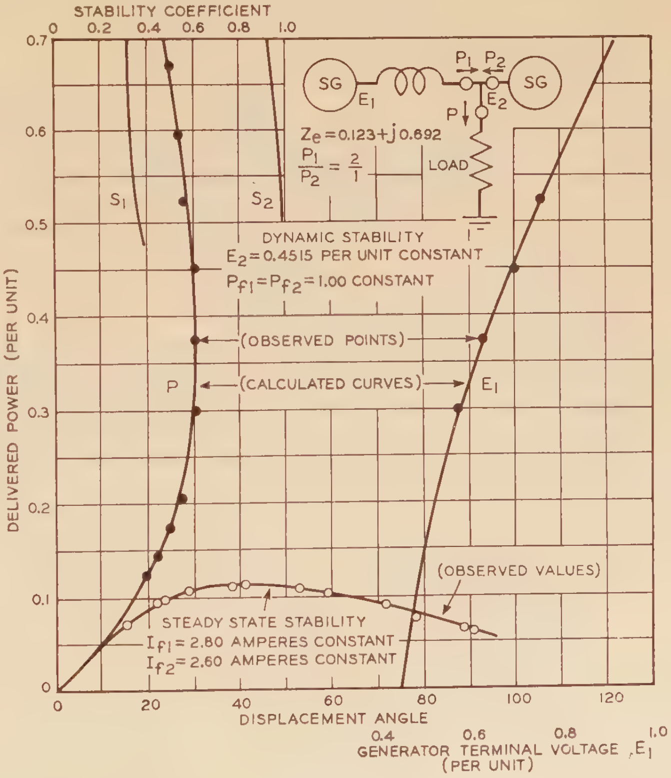


**Figure 9. Steady-state and dynamic power limits of a two-generator system including series impedance and variable shunt load**

one line in service. With the exception of the generator quadrature reactances, actual system constants were used.[12]

Several times during emergency switching and trip-outs, full load (approximately 77,000 kw) was dumped on the remaining line for a few minutes until the station operators had time to readjust the governors. It was reported that although there was naturally quite a disturbance when one line went out, (depending upon the severity and location of the trouble) in no case was there any indication of instability when one line was carrying the load. This is consistent with the calculated value and should increase confidence in the proposed analysis.

### Boulder Dam System

The dynamic power limit of the Boulder Dam-City of Los Angeles system should be of considerable importance, since the system originally designed for a transient stability limit of 235,000 kw has already carried peak loads of approximately 281,000 kw. System data were taken from Scattergood's paper,[13] and supplemented with the actual quadrature reactances of the Boulder Dam generators. The equivalent steam-plant impedances were assumed by the writer. The Los Angeles load was assumed at 0.80 power factor lagging and the theoretical synchronous condenser kva required to maintain the system voltages was computed. Using a factor of 0.80 to allow for imperfections in assumptions, system hunting, etc., the dynamic delivered power limit of the 275-kv transmission system was approximately 294,000 kw with the steam plant floating. The power limit increased materially as the steam plant was given load. It may be interesting to mention that similar studies using round-rotor theory and neglecting saturation lowered the theoretical dynamic power limit 43,000 kw. Perhaps a more important problem involves the dynamic power limit with one line section out of service; however, lack of time prevented extended investigation.

The above examples and practical problems should be sufficient to illustrate the application of the static stability limits of power systems. It is believed that the effects of saliency and saturation are of sufficient importance to warrant consideration, especially for practical cases where an accurate determination of the maximum power limits are under question.

## Appendix I

### Derivation of Power-Angle Equations

The following is an extension of the familiar power-angle equations. Lower-case bold-face letters are used to denote

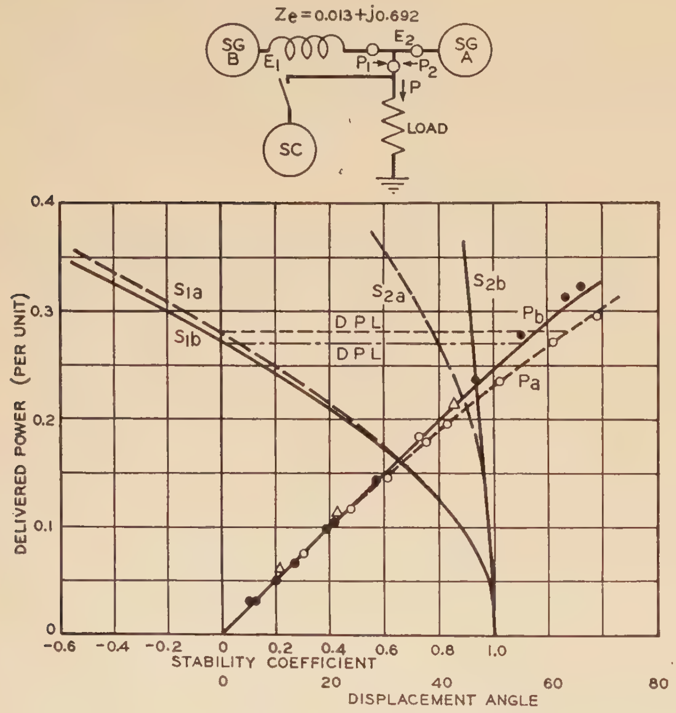


**Figure 10. Dynamic power limits of a two-generator system including series impedance and variable shunt load**

Subscript *a* denotes data obtained with no condenser

Subscript *b* denotes data obtained using condensers

Generator *A* excitation varied to hold $Pf_2$ at unity

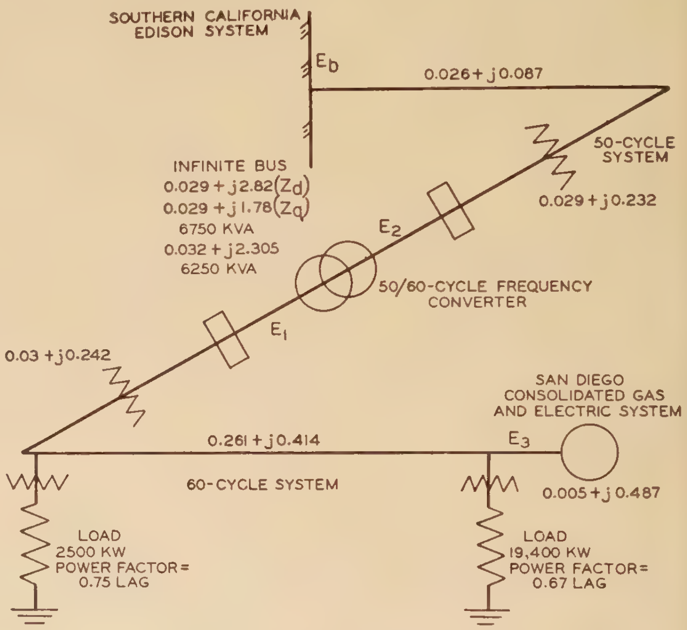
$E_1 = E_2 = 0.4515$ constant

△ Points obtained using a static condenser in place of the synchronous condenser

*DPL*—Dynamic power limit

*SC*—Synchronous condenser

**Figure 11. Factors controlling power limit of system**


SOUTHERN CALIFORNIA EDISON SYSTEM
Eb
0.026+j0.087
50-CYCLE SYSTEM
INFINITE BUS
0.029+j2.82(Zd)
0.029+j1.78(Zq)
6750 KVA
0.032+j2.305
6250 KVA
E2
0.029+j0.232
50/60-CYCLE FREQUENCY CONVERTER
E1
0.03+j0.242
SAN DIEGO CONSOLIDATED GAS AND ELECTRIC SYSTEM
0.261+j0.414
E3
60-CYCLE SYSTEM
0.005+j0.487
LOAD 2500 KW POWER FACTOR= 0.75 LAG
LOAD 19,400 KW POWER FACTOR= 0.67 LAG

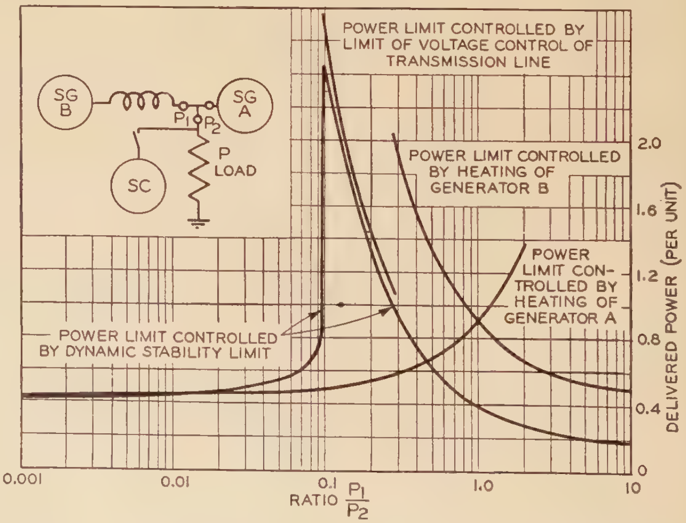


**Figure 12. San Diego Consolidated Gas and Electric-Southern California Edison interconnected system**

System impedances on 20,000-kva base

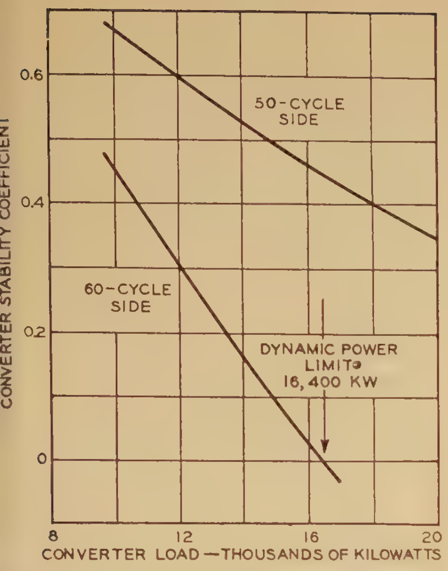


**Figure 13. Dynamic power limits of 50/60-cycle converter**

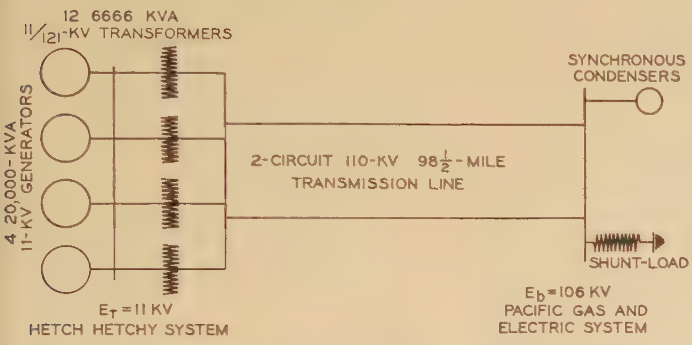


**Figure 14. Hetch Hetchy-Pacific Gas and Electric interconnected system**

vectors, and capitals represent scalars. Subscript $q$ used with current or voltages represents the quadrature-axis component; similarly, subscript $d$ denotes the direct-axis component. The first numerical subscript following $q$ or $d$ refers to the voltage producing that current. The second numerical subscript, or when only one subscript is used, denotes the branch or machine considered. Subscripts $q$ or $d$ used with reactance refer to the synchronous-machine constants according to present usage. The system impedances are denoted by a double subscript notation consistent with the above.[2,5,6,10,14]

Referring to figure 1, the shaft power output of machine 1 is:

$$P_1 = E_{q1} I_{q1} \tag{1}$$

By the principle of superposition

$$I_{q1} = I_{q11} - I_{q21} \ldots - I_{qn1} \tag{2}$$

$$I_{d1} = I_{d11} - I_{d21} \ldots - I_{dn1} \tag{3}$$

also

$$\mathbf{i}_{11} = \frac{\mathbf{e}_{q1}}{\mathbf{z}_{11}},\ \mathbf{i}_{21} = \frac{\mathbf{e}_{q2}}{\mathbf{z}_{21}},\ \ldots\ \mathbf{i}_{n1} = \frac{\mathbf{e}_{n}}{\mathbf{z}_{n1}}$$

The impedances contain the system parameters, machine resistance, and the quadrature-axis synchronous reactance. Obviously the scalar value of $Z_{1n} = Z_{n1}$, and $\phi_{1n} = \phi_{n1}$. Let $\delta_n$ be the angle of $\mathbf{e}_{qn}$ from a reference.

$$\delta_{1n} = \delta_1 - \delta_n$$

Introducing scalars:

$$I_{q11} = \frac{E_{q1}}{Z_{11}} \cos\phi_{11},\ I_{q21} = \frac{E_{q2}}{Z_{12}} \cos(\delta_{12} + \phi_{12}),\ ..$$

$$\ldots I_{qn1} = \frac{E_{qn}}{Z_{1n}} \cos(\delta_{1n} + \phi_{1n})$$

and

$$I_{d11} = \frac{E_{q1}}{Z_{11}} \sin\phi_{11},\ I_{d21} = \frac{E_{q2}}{Z_{12}} \sin(\delta_{12} + \phi_{12}),\ ..$$

$$\ldots I_{dn1} = \frac{E_{qn}}{Z_{1n}} \sin(\delta_{1n} + \phi_{1n})$$

Substituting $\alpha_{1n} = 90 - \phi_{1n}$ in the foregoing:

$$I_{q1} = \frac{E_{q1}}{Z_{11}} \sin\alpha_{11} + \frac{E_{q2}}{Z_{12}} \sin(\delta_{12} - \alpha_{12}) \ldots + \frac{E_{qn}}{Z_{1n}} \sin(\delta_{1n} - \alpha_{1n}) \tag{4}$$

and

$$I_{d1} = \frac{E_{q1}}{Z_{11}} \cos\alpha_{11} - \frac{E_{q2}}{Z_{12}} \cos(\delta_{12} - \alpha_{12}) \ldots - \frac{E_{qn}}{Z_{1n}} \cos(\delta_{1n} - \alpha_{1n}) \tag{5}$$

Substituting (4) in (1):

$$P_1 = \frac{E_{q1}^2}{Z_{11}} \sin\alpha_{11} + \frac{E_{q1}E_{q2}}{Z_{12}} \sin(\delta_{12} - \alpha_{12}) + \frac{E_{q1}\,E_{q3}}{Z_{13}} \sin(\delta_{13} - \alpha_{13}) \ldots + \frac{E_{q1}\,E_{qn}}{Z_{1n}} \sin(\delta_{1n} - \alpha_{1n})$$

Similarly,

$$P_k = \frac{E_{qk}^2}{Z_{kk}} \sin\alpha_{kk} + \frac{E_{qk}E_{q1}}{Z_{k1}} \sin(\delta_{k1} - \alpha_{k1}) + \frac{E_{qk}\,E_{q2}}{Z_{k2}} \sin(\delta_{k2} - \alpha_{k2}) \ldots + \frac{E_{qk}E_{qn}}{Z_{kn}} \sin(\delta_{kn} - \alpha_{kn}) \tag{6}$$

The relation between $E_1$ and $E_q$ is apparent from figure 1:

$$E_{t1} = E_{q1} + I_{d1}(X_{d1} - X_{q1})$$

Substituting equation 5:

$$E_{t1} = E_{q1}\left(1 + \frac{(X_{d1} - X_{q1})}{Z_{11}} \cos\alpha_{11}\right) - E_{q2}\frac{(X_{d1} - X_{q1})}{Z_{12}} \cos(\delta_{12} - \alpha_{12}) \ldots - E_{qn}\frac{(X_{d1} - X_{q1})}{Z_{1n}} \cos(\delta_{1n} - \alpha_{1n})$$

Let

$$A_1 = 1 + \frac{(X_{d1} - X_{q1})}{Z_{11}} \cos\alpha_{11}$$

$$A_n = 1 + \frac{(X_{dn} - X_{qn})}{Z_{nn}} \cos\alpha_{nn}$$

$$B_{12} = \frac{(X_{d1} - X_{q1})}{Z_{12}}$$

$$B_{kn} = \frac{(X_{dk} - X_{qk})}{Z_{kn}}$$

Then

$$E_{t1} = A_1E_{q1} - E_{q2}B_{12}\cos(\delta_{12} - \alpha_{12}) - E_{q3}B_{13}\cos(\delta_{13} - \alpha_{13}) \ldots - E_{qn}B_{1n}\cos(\delta_{1n} - \alpha_{1n})$$

Similarly

$$E_{tk} = -E_{q1}B_{k1}\cos(\delta_{k1} - \alpha_{k1}) \ldots + A_kE_{qk} \ldots - E_{qn}B_{kn}\cos(\delta_{kn} - \alpha_{kn}) \tag{7}$$

Values of $E_{q1}, E_{q2}, E_{qk} \ldots E_{qn}$, are obtained from simultaneous solution of these equations, for example, see equation 8.

$$E_{qk} = \frac{\begin{vmatrix} A_1 & -B_{12}\cos(\delta_{12} - \alpha_{12}) & \ldots. & E_{t1} & \ldots. & -B_{1n}\cos(\delta_{1n} - \alpha_{1n}) \\ -B_{21}\cos(\delta_{21} - \alpha_{21}) & A_2 & \ldots. & E_{t2} & \ldots. & -B_{2n}\cos(\delta_{2n} - \alpha_{2n}) \\ \ldots. & \ldots. & \ldots. & \ldots. & \ldots. & \ldots. \\ -B_{k1}\cos(\delta_{k1} - \alpha_{k1}) & -B_{k2}\cos(\delta_{k2} - \alpha_{k2}) & \ldots. & E_{tk} & \ldots. & -B_{kn}\cos(\delta_{kn} - \alpha_{kn}) \\ \ldots. & \ldots. & \ldots. & \ldots. & \ldots. & \ldots. \\ -B_{n1}\cos(\delta_{n1} - \alpha_{n1}) & -B_{n2}\cos(\delta_{n2} - \alpha_{n2}) & \ldots. & E_{tn} & \ldots. & A_n \end{vmatrix}}{\begin{vmatrix} A_1 & -B_{12}\cos(\delta_{12} - \alpha_{12}) & \ldots. & -B_{1k}\cos(\delta_{1k} - \alpha_{1k}) & \ldots. & -B_{1n}\cos(\delta_{1n} - \alpha_{1n}) \\ -B_{21}\cos(\delta_{21} - \alpha_{21}) & A_2 & \ldots. & -B_{2k}\cos(\delta_{2k} - \alpha_{2k}) & \ldots. & -B_{2n}\cos(\delta_{2n} - \alpha_{2n}) \\ \ldots. & \ldots. & \ldots. & \ldots. & \ldots. & \ldots. \\ -B_{k1}\cos(\delta_{k1} - \alpha_{k1}) & -B_{k2}\cos(\delta_{k2} - \alpha_{k2}) & \ldots. & A_k & \ldots. & -B_{kn}\cos(\delta_{kn} - \alpha_{kn}) \\ \ldots. & \ldots. & \ldots. & \ldots. & \ldots. & \ldots. \\ -B_{n1}\cos(\delta_{n1} - \alpha_{n1}) & -B_{n2}\cos(\delta_{n2} - \alpha_{n2}) & \ldots. & -B_{nk}\cos(\delta_{nk} - \alpha_{nk}) & \ldots. & A_n \end{vmatrix}} \tag{8}$$

The power equations for the two machines are obtained from equation 6. Substituting ${}_2\delta_1 = -\delta_{12}$ and rearranging:

$$\left.\begin{aligned} P_1 &= \frac{E_{q1}{}^2}{Z_{11}} \sin \alpha_{11} + \frac{E_{q1}E_{q2}}{Z_{12}} \sin (\delta_{12} - \alpha_{12}) \\ P_2 &= \frac{E_{q2}{}^2}{Z_{22}} \sin \alpha_{22} - \frac{E_{q1}E_{q2}}{Z_{12}} \sin (\delta_{12} + \alpha_{12}) \end{aligned}\right\} \quad (9)$$

From equation 7:

$$E_{t1} = A_1E_{q1} - E_{q2}B_{12} \cos (\delta_{12} - \alpha_{12})$$

$$E_{t2} = -E_{q1}B_{21} \cos (\delta_{12} + \alpha_{12}) + A_2E_{q2}$$

Solving for $E_{q1}$ and $E_{q2}$ and simplifying:

$$\left.\begin{aligned} E_{q1} &= \frac{A_2E_{t1} + E_{t2}B_{12} \cos (\delta_{12} - \alpha_{12})}{A_1A_2 + B_{21}B_{12} \sin^2 \alpha_{12} - B_{21}B_{12} \cos^2 \delta_{12}} \\ E_{q2} &= \frac{A_1E_{t2} + E_{t1}B_{21} \cos (\delta_{12} + \alpha_{12})}{A_1A_2 + B_{21}B_{12} \sin^2 \alpha_{12} - B_{21}B_{12} \cos^2 \delta_{12}} \end{aligned}\right\} \quad (10)$$

Substituting equation 10 in equation 9 gives the power-angle equations for two salient-pole machines. The stability coefficients are determined by differentiation. Only significant terms are included. Common multiplying factors and terms becoming negligible at the maximum power output have been omitted.

### POWER-ANGLE EQUATIONS FOR TWO SALIENT-POLE MACHINES

The shaft power output of the leading machine is:

$$P_1 = \left[\frac{A_2E_{t1} + E_{t2}B_{12} \cos (\delta_{12} - \alpha_{12})}{A_1A_2 + B_{12}B_{21} \sin^2 \alpha_{12} - B_{12}B_{21} \cos^2 \delta_{12}}\right]^2 \frac{\sin \alpha_{11}}{Z_{11}} + \left[\frac{A_2E_{t1} + E_{t2}B_{12} \cos (\delta_{12} - \alpha_{12})}{A_1A_2 + B_{12}B_{21} \sin^2 \alpha_{12} - B_{12}B_{21} \cos^2 \delta_{12}}\right] \times \left[\frac{A_1E_{t2} + E_{t1}B_{21} \cos (\delta_{12} + \alpha_{12})}{A_1A_2 + B_{12}B_{21} \sin^2 \alpha_{12} - B_{12}B_{21} \cos^2 \delta_{12}}\right] \frac{\sin (\delta_{12} - \alpha_{12})}{Z_{12}}$$

The stability coefficient of the leading machine is:

$$S_1 = A_1A_2E_{t1}E_{t2} \cos (\delta_{12} - \alpha_{12}) + A_1E_{t2}{}^2B_{12} \cos 2(\delta_{12} - \alpha_{12}) + A_2E_{t1}{}^2B_{21} \cos 2\delta_{12} - 2A_2E_{t1}E_{t2}B_{12} \frac{Z_{12}}{Z_{11}} \sin \alpha_{11} \sin (\delta_{12} - \alpha_{12}) \quad (11)$$

The shaft power output of the lagging machine is:

$$P_2 = \left[\frac{A_1E_{t2} + E_{t1}B_{21} \cos (\delta_{12} + \alpha_{12})}{A_1A_2 + B_{12}B_{21} \sin^2 \alpha_{12} - B_{12}B_{21} \cos^2 \delta_{12}}\right]^2 \frac{\sin \alpha_{22}}{Z_{22}} - \left[\frac{A_2E_{t1} + E_{t2}B_{12} \cos (\delta_{12} - \alpha_{12})}{A_1A_2 + B_{12}B_{21} \sin^2 \alpha_{12} - B_{12}B_{21} \cos^2 \delta_{12}}\right] \times \left[\frac{A_1E_{t2} + E_{t1}B_{21} \cos (\delta_{12} + \alpha_{12})}{A_1A_2 + B_{12}B_{21} \sin^2 \alpha_{12} - B_{12}B_{21} \cos^2 \delta_{12}}\right] \frac{\sin (\delta_{12} + \alpha_{12})}{Z_{12}}$$

The stability coefficient of the lagging machine is:

$$S_2 = A_1A_2E_{t1}E_{t2} \cos (\delta_{12} + \alpha_{12}) + A_2E_{t1}{}^2B_{21} \cos 2(\delta_{12} + \alpha_{12}) + A_1E_{t2}{}^2B_{12} \cos 2\delta_{12} + 2A_1E_{t1}E_{t2}B_{21} \frac{Z_{12}}{Z_{22}} \sin \alpha_{22} \sin (\delta_{12} + \alpha_{12}) \quad (12)$$

Where: $\delta_{12}$ is the displacement angle between the axes of machines 1 and 2 in electrical degrees. $Z_{11}$, $Z_{22}$, and $Z_{12}$ are the driving point, receiving point, and transfer impedances, respectively, and contain $X_q$ of the machines. $\alpha_{11}$, $\alpha_{22}$, and $\alpha_{12}$ are their associated angles ($\alpha = 90 - \phi_z$). In most cases the $\alpha$ angles are small, and the output of a generator is positive; similarly, the output of a motor is negative.

When the machines have round rotors the $A$ constants become unity, the $B$ terms zero, and the machine $X_q = X_d$, $E_t = E_d$.

### POWER-ANGLE EQUATIONS FOR TWO ROUND-ROTOR MACHINES

$$P_1 = E_{d1}{}^2 \frac{\sin \alpha_{11}}{Z_{11}} + \frac{E_{d1}E_{d2}}{Z_{12}} \sin (\delta_{12} - \alpha_{12}) \qquad S_1 = \cos (\delta_{12} - \alpha_{12}) \quad (13)$$

$$P_2 = E_{d2}{}^2 \frac{\sin \alpha_{22}}{Z_{22}} - \frac{E_{d1}E_{d2}}{Z_{12}} \sin (\delta_{12} + \alpha_{12}) \qquad S_2 = \cos (\delta_{12} + \alpha_{12}) \quad (14)$$

These equations are recognized as the familiar round-rotor power equations. They may be used to determine the power transfer between two round-rotor machines, or any two points of known voltage, $E_{d1}$ and $E_{d2}$.

## Appendix II

### Derivation of Current Equations

The machine currents are given by equations 4 and 5. Similarly, the voltages are obtained from equation 7 or 8. The machine currents for the two-machine case are derived as follows:

The component currents of machine 1 are:

$$I_{q1} = \frac{E_{q1}}{Z_{11}} \sin \alpha_{11} + \frac{E_{q2}}{Z_{12}} \sin (\delta_{12} - \alpha_{12})$$

$$I_{d1} = \frac{E_{q1}}{Z_{11}} \cos \alpha_{11} - \frac{E_{q2}}{Z_{12}} \cos (\delta_{12} - \alpha_{12}) \quad (15)$$

and the component currents of machine 2 are:

$$I_{q2} = \frac{E_{q2}}{Z_{22}} \sin \alpha_{22} - \frac{E_{q1}}{Z_{12}} \sin (\delta_{12} + \alpha_{12})$$

$$I_{d2} = \frac{E_{q2}}{Z_{22}} \cos \alpha_{22} - \frac{E_{q1}}{Z_{12}} \cos (\delta_{12} + \alpha_{12}) \quad (16)$$

Substituting $E_{q1}$ and $E_{q2}$ from equation 10 in equations 15 and 16 gives the—

### CURRENT-ANGLE EQUATIONS FOR TWO SALIENT-POLE MACHINES

The quadrature-axis component of current of the leading machine is:

$$I_{q1} = \left[\frac{A_2E_{t1}+E_{t2}B_{12} \cos (\delta_{12}-\alpha_{12})}{A_1A_2+B_{12}B_{21} \sin^2 \alpha_{12}-B_{12}B_{21} \cos^2 \delta_{12}}\right] \times \frac{\sin \alpha_{11}}{Z_{11}} + \left[\frac{A_1E_{t2}+E_{t1}B_{21} \cos (\delta_{12}+\alpha_{12})}{A_1A_2+B_{12}B_{21} \sin^2 \alpha_{12}-B_{12}B_{21} \cos^2 \delta_{12}}\right] \times \frac{\sin (\delta_{12} - \alpha_{12})}{Z_{12}}$$

The direct axis component of current of the leading machine is:

$$I_{d1} = \left[\frac{A_2E_{t1} +E_{t2}B_{12} \cos (\delta_{12}-\alpha_{12})}{A_1A_2+B_{12}B_{21} \sin^2 \alpha_{12}-B_{12}B_{21} \cos^2 \delta_{12}}\right] \times \frac{\cos \alpha_{11}}{Z_{11}} - \left[\frac{A_1E_{t2}+E_{t1}B_{21} \cos (\delta_{12}+\alpha_{12})}{A_1A_2+B_{12}B_{21} \sin^2 \alpha_{12}-B_{12}B_{21} \cos^2 \delta_{12}}\right] \times \frac{\cos (\delta_{12} - \alpha_{12})}{Z_{12}}$$

The total current is:

$$I_1 = \sqrt{I_{q1}{}^2 + I_{d1}{}^2} \quad (17)$$

at an angle $= \tan^{-1} I_{d1}/I_{q1}$ from the axis of machine 1.

The quadrature-axis component of current of the lagging machine is:

$$I_{q2} = \left[\frac{A_1E_{t2}+E_{t1}B_{21} \cos (\delta_{12}+\alpha_{12})}{A_1A_2+B_{12}B_{21} \sin^2 \alpha_{12}-B_{12}B_{21} \cos {}^2\delta_{12}}\right] \times \frac{\sin \alpha_{22}}{Z_{22}} - \left[\frac{A_2E_{t1}+E_{t2}B_{12} \cos (\delta_{12}-\alpha_{12})}{A_1A_2+B_{12}B_{21} \sin^2 \alpha_{12}-B_{12}B_{21} \cos^2 \delta_{12}}\right] \times \frac{\sin (\delta_{12} + \alpha_{12})}{Z_{12}}$$

nd

$$I_{d2} = \left[\frac{A_1E_{i2}+E_{i2}B_{12}\cos(\delta_{12}+\alpha_{12})}{A_1A_2+B_{12}B_{21}\sin^2\alpha_{12}-B_{12}B_{21}\cos^2\delta_{12}}\right]\times \frac{\cos\alpha_{22}}{Z_{22}} - \left[\frac{A_2E_{i1}+E_{i1}B_{21}\cos(\delta_{12}-\alpha_{12})}{A_1A_2+B_{12}B_{21}\sin^2\alpha_{12}-B_{12}B_{21}\cos^2\delta_{12}}\right]\times \frac{\cos(\delta_{12}+\alpha_{12})}{Z_{12}}$$

$$I_2 = \sqrt{I_{q2}^2 + I_{d2}^2} \quad \text{at an angle} = \tan^{-1} I_{d2}/I_{q2} \qquad (18)$$

When the machines have round rotors he $A$ constants = 1, the $B$ constants = 0, he machine $X_q = X_d$, and $E_i = E_d$.

### Current-Angle Equations for Two Round-Rotor Machines

$$I_{q1} = \frac{E_{d1}\sin\alpha_{11}}{Z_{11}} + \frac{E_{d2}\sin(\delta_{12}-\alpha_{12})}{Z_{12}}$$

$$I_{d1} = \frac{E_{d1}\cos\alpha_{11}}{Z_{11}} - \frac{E_{d2}\cos(\delta_{12}-\alpha_{12})}{Z_{12}}$$

$$I_1 = \sqrt{I_{q1}^2 + I_{d1}^2} \quad \text{at an angle} = \tan^{-1} I_{d1}/I_{q1} \qquad (19)$$

nd

$$I_{q2} = \frac{E_{d2}\sin\alpha_{22}}{Z_{22}} - \frac{E_{d1}\sin(\delta_{12}+\alpha_{12})}{Z_{12}}$$

$$I_{d2} = \frac{E_{d2}\cos\alpha_{22}}{Z_{22}} - \frac{E_{d1}\cos(\delta_{12}+\alpha_{12})}{Z_{12}}$$

$$I_2 = \sqrt{I_{q2}^2 + I_{d2}^2} \quad \text{at an angle} = \tan^{-1} I_{d2}/I_{q2} \qquad (20)$$

It should be noted that the component currents refer to the axes of the particular machine considered, see figure 1.

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## Discussion

**S. B. Crary** (General Electric Company, Schenectady, N. Y.): The experimental checks which the author has obtained are very good and appear to substantiate his conclusion "that for practical purposes static stability may be regarded as a problem of stable equilibrium in which all transient phenomena and inertia effects may be neglected (reference 2)." However, as the author's experimental results necessarily only covered a very limited range, it is desirable to view any general conclusions drawn directly from such experiments quite critically. Mr. Dalziel's reference 2 presents a conservative method for determining the stability limit which has great practical value when applied with a knowledge of the conditions under which the results may be too conservative. Discussions of the limitations of the method may be found on pages 475, 476, 601, and 602, AIEE Transactions, volume 53, 1934. An example of a case in which the inertia effects are important is a large generator delivering load to a large shunt load of constant impedance and a small synchronous motor. Actually the angular displacement between the motor and generator may approach 180 degrees with stable operation. Such a conclusion may be reached analytically when the relative inertia of the generator and motor are considered.

Reference is also made in the paper to the report of the AIEE subcommittee on stability (reference 3), to substantiate the contention that the inertia effects may be neglected. The subcommittee report must have been unintentionally misleading to the extent that it was possible for Mr. Dalziel to misinterpret it in this respect.

The following statement is made in the paper "For cases in which the system voltages are maintained constant, all shunt loads including synchronous condensers and induction motors may be accurately represented by simple shunt impedances. This treatment assumes that the induction portion of the system load remains stable. Since the maximum power transfer is ordinarily limited by the synchronous machine on the system, this assumption should not introduce errors in the result (reference 7)." That such a simplification cannot be made in many practical studies is well known and reference 7 does not show that this is possible. Reference 7 does show that a composite load may be replaced with good approximation by an equivalent load having a given real and reactive power and a given rate of change of real power and reactive power with voltage. These four characteristics are sufficient in order to obtain the effect of a composite load on the system. However, only when the rate of change of real and reactive power with respect to voltage are related to the total amount of real and reactive power in a definite manner can the composite load be replaced by a simple shunt impedance. This unfortunately is the exception rather than the rule. The case of fixed impedance load rather than the actual characteristics of a composite load will in general lead to optimistic or too high steady-state stability limits as the real power component of a composite load does not fall off or decrease as rapidly as that of a constant shunt impedance with drop in voltage.

**A. J. Gilardi** (Ohio Brass Company, Barberton): I should like to supplement Professor Dalziel's consideration of the Hetch Hetchy-Pacific Gas and Electric system by a concrete example which incidentally includes typical stability curves of the power system.

For accurate analysis equations 11 and 12 of the paper should be used to calculate the steady-state power limits. The steady-state power curve and margin of stability so determined accurately considers saliency and saturation. However, since the transmission line under consideration has considerable series impedance it will be sufficiently accurate to compute the steady-state power curve using $X_{q\ sat}$ in equations 13 and 14. In figures 3 and 4 of the paper it is shown that the error due to neglecting saliency decreases with increased system impedance. The simplification obtained by neglecting saliency greatly reduces the labor of computation and the resulting errors are small. The steady-state power limits and stability coefficients computed using 0.90 $X_{q\ unsat}$ in determining $S_1$ and $S_2$ from equations 13 and 14 gives results which are approximately correct where accuracy is not essential (i.e., at the large margins of stability) and accurate results at the power limit where good accuracy is desired.

The accompanying figure 1 illustrates the power system under consideration, except that only one circuit of the transmission line was used in the computations. The receiving-end bus feeds a shunt load

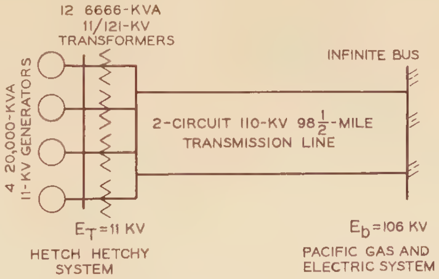

Figure 1. Hetch Hetchy-Pacific Gas and Electric interconnected system

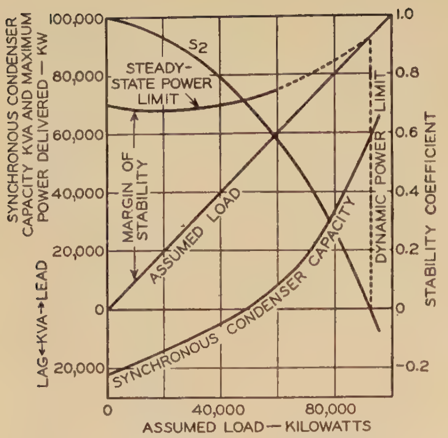

**Figure 2. Steady-state and dynamic power limits of Hetch Hetchy system**

and the synchronous condenser serves to maintain constant voltages on the system. The following equations were used to determine the stability limits utilizing the simplifications of the preceding paragraph:

$$P_1 = \frac{e_{q1}^2}{Z_{11}} \sin \alpha_{11} + \frac{e_{q1}E_b}{Z_{12}} \sin (\delta_{12} - \alpha_{12}) \quad (1)$$

$$S_1 = \cos(\delta_{12} - \alpha_{12}) \quad (2)$$

$$P_2 = \frac{E_b^2 \sin \alpha_{22}}{Z_{22}} - \frac{e_{q1}E_b}{Z_{12}} \sin (\delta_{12} + \alpha_{12}) \quad (3)$$

$$S_2 = \cos (\delta_{12} + \alpha_{12}) \quad (4)$$

Since $\alpha_{12}$ is positive the power limits are determined by $P_2$ and $S_2$. The results of computations for various loads using the foregoing equations are shown in figure 2. These results were obtained using actual system constants with the exception of the generator reactances. The curve for $S_1$ is not shown since $S_2$ reaches zero first. The synchronous-condenser kilovolt-ampere curve indicates the amount of capacity required to maintain constant system voltage at any given load. It may be seen that the dynamic power limit is approximately 92,500 kw with one line in service. As mentioned in the paper one line has delivered approximately 77,000 kw during emergency switching and trip-outs.

Figure 3 compares the margin of stability of figure 2 with that obtained for the same system using the unsaturated cylindrical-rotor theory. It is evident that the latter approach gives only an approximate solution which is less accurate than by using the theory outlined in the paper.

**Charles F. Dalziel:** The author wishes to thank S. B. Crary for the constructive comments drawn from his rich experience in this field. The final draft of the paper has been changed in an endeavor to meet his objections regarding the representation of loads. It was originally intended to check the method and the simplifying assumptions under question by comparing theoretical results with the operating records of several large power systems. The analyses of the practical problems presented in the paper are consistent and in good agreement with available operating records. However, due to limited data, the results fall somewhat short of the original objective. The writer would appreciate receiving system data for cases where the stability limits are fairly accurately known, and which could be reduced to a two-generator system for analysis.

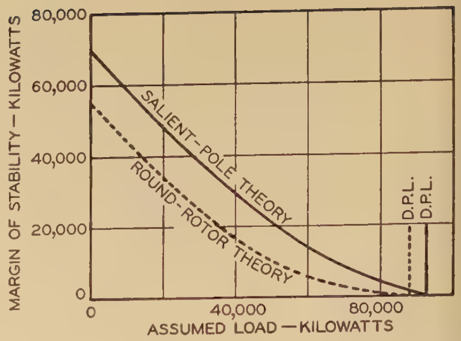

**Figure 3. Comparison of results obtained by use of round-rotor or salient-pole theory**

Mr. Gilardi's detailed analysis of the Hetch Hetchy system should be of interest to those applying the method to actual systems. It should be repeated that most of the generator impedances in the practical problems were unknown, and typical average values were used. These were multiplied by 0.90 to give an approximate correction for saturation. This may explain the small effect of saliency and saturation on Mr. Gilardi's power limits in contrast to the experimental differences of figure 8.

# Applications of Copper-Oxide Rectifiers

By E. W. MORRIS
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**Synopsis:** Since the development of the copper-oxide rectifier in 1927, no paper has presented to the Institute a comprehensive list of the many problems to which the device may be applied successfully. It is the purpose of this paper to describe a few of the representative installations made in the various industries.

WHEN the copper-oxide rectifier was announced,[1] limited information was available regarding such characteristics as aging, the effect of ambient temperatures, and the safe values of current and voltage per disk. Applications made since 1927 have removed many of these uncertainties. Continued research has produced valuable information about the characteristics of the device, and has improved the method of manufacture and application to industry.[2,3] It has become indispensable in the design of control and electronic equipment,[4] and is well adapted to applications requiring high efficiency at low voltage and to those requiring high overload capacities for short periods of time.

The copper-oxide rectifier consists essentially of a copper disk, one side of which is covered with cuprous oxide formed by heating to a high temperature. This rectifier disk then has the characteristics of asymmetric resistance, allowing electrons to pass more readily from copper to oxide than in the reverse direction, as indicated in figure 1. The rating of a disk is based upon ability to dissipate the losses, and rectifier disks usually are assembled into units with cooling fins and spacers to assist in heat dissipation. Soft metal washers insure intimate contact with the oxide.

These assembled units may be connected into groups for half- and full-wave rectification, for any number of phases, and in parallel or series for increased current or voltage ratings.

As valves in d-c control circuits they are convenient in isolation of circuits, preventing current flow in reverse directions to a common bus.

Applications of copper-oxide disks made during the past ten years can be classified as rectifiers for battery loads, rectifiers for resistance loads, and valves in control circuits.

## I. Rectifiers for Battery Loads

After the development of the copper-oxide rectifier, one of the most immediate applications was that of small battery chargers. Sizes of chargers have gradually increased until now they are available in ratings up to 6 amperes at 130 volts. A duplex charger having a rating of 15 amperes at 30 volts and 0.5 ampere at 24 volts is shown in figure 2. Simplicity results in an assembly consisting of an insulating transformer, the copper-oxide rectifying units, some type of overload protection, and a dial switch to care for current adjustment and aging.

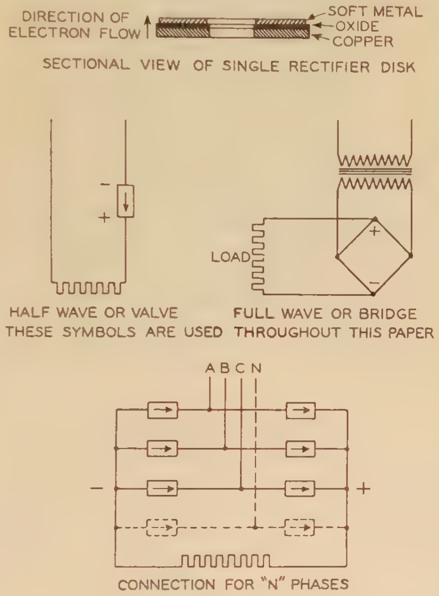
DIRECTION OF ELECTRON FLOW
SOFT METAL
OXIDE
COPPER
SECTIONAL VIEW OF SINGLE RECTIFIER DISK
−
+
LOAD
+
−
HALF WAVE OR VALVE
FULL WAVE OR BRIDGE
THESE SYMBOLS ARE USED THROUGHOUT THIS PAPER
A B C N
−
+
CONNECTION FOR "N" PHASES

Figure 1

The nearest approach to an ideal battery charger has been obtained in the recent development of a self-regulating charger, the diagram of which is shown in figure 3. It is particularly adaptable for floating battery service, and automatically varies the charging rate proportionate with the demands of the battery by means of saturable reactors. The main rectifier, I, furnishes charging current to the battery. Between the transformer secondary and the main rectifier is located a saturable reactor, *A*. The saturation of reactor *A* is controlled partly by a series coil which is energized by the charging current, partly by a shunt coil, but mainly by rectifier II. This rectifier is supplied from the primary side of the transformer through a second saturable reactor, *B*. Rectifier III is furnished with a constant a-c voltage by means of a small regulator connected across the primary of the power transformer. The constant d-c output voltage of rectifier III is opposed by the battery voltage so that any difference between the two will result in a flow of current through the d-c winding of reactor *B;* hence the saturation of reactor *B* will vary according to the battery voltage. Reduction in the cell

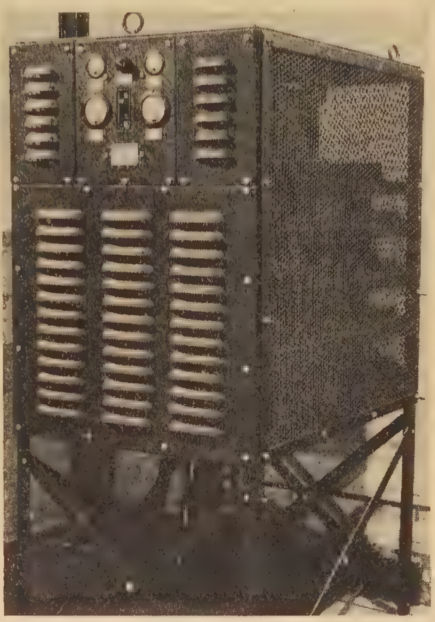

Figure 2. Station-type rectifier for charging telephone batteries

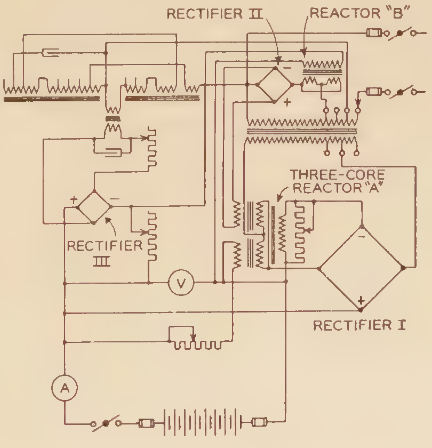

Figure 3. Automatic self-regulating battery charger

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[1] For all numbered references, see list at end of paper.

voltage below the average for which the charger is set to regulate will cause the charger to turn on and deliver full charging current to the battery. As the cell voltage increases to a point above the average voltage, the charging current will be reduced to its minimum value. Such a charger is capable of maintaining the cell voltage within limits of plus or minus one per cent for all load conditions and for variations in the a-c line voltage of not more than plus or minus five per cent.

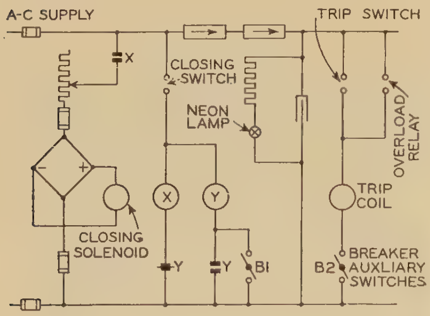


**Figure 4. Circuit breaker closing and tripping from an a-c supply**

## II. Rectifiers for Resistance Loads

In the field of industrial control, versatility has been added by the use of the copper-oxide rectifier. The advantages of d-c operation of contactors and relays can be obtained from an a-c source and the rectifying units. D-c fields can be excited from an a-c supply and regulated by means of the proper arrangement of rectifiers and reactors.

### Rectifiers for Circuit-Breaker Operation

Solenoid type of circuit-breaker mechanisms may be operated from an a-c source by means of rectifiers connected as in figure 4. Operation of the closing switch energizes relay *X*, which in turn energizes the rectifier and the closing solenoid. The circuit breaker, in closing, closes pallet switch *B*1, thus energizing relay *Y*, which seals in as long as the contacts of the closing switch are held in the closed position. The operation of relay *Y* de-energizes relay *X* and the rectifier, providing an automatic cutoff. Since the rating of the rectifier is limited by its thermal capacity and ability to dissipate internal heat, it has a high short-time overload capacity, and is ideal for this type of application. Circuit breakers may be tripped from an a-c source by the use of rectifiers and capacitors, a distinct advantage in the elimination of battery maintenance at isolated or unattended substations. Capacitor tripping has the advantage of requiring current transformers only of sufficient size to energize the fault-detector relays. The tripping energy is stored in capacitors from the a-c supply voltage during normal conditions, and is available to trip the breaker for at least six seconds after charging potential is entirely removed. In figure 4, when the overload relay or manual tripping contacts close, the capacitor discharges through the trip coil. The device is so designed that sufficient charge is available to trip the breaker at any time with not less than 65 per cent of normal potential. The tripping capacitor will recharge in 0.2 second. Figure 5 shows, in the lower left-hand corner, the small size of rectifier required to close a 5,000-ampere three-pole air circuit breaker.

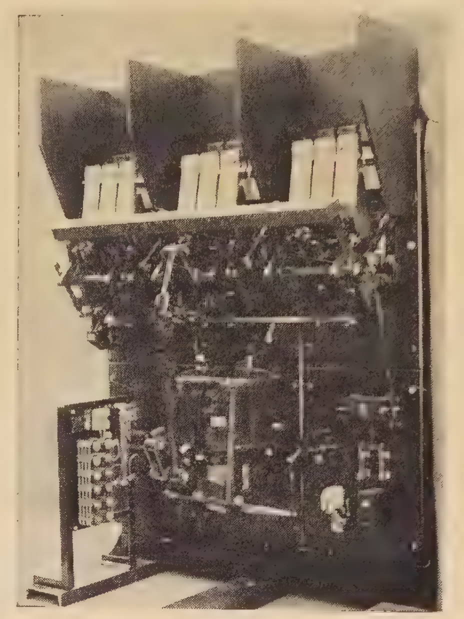


**Figure 5. A 5,000-ampere circuit breaker with solenoid closing mechanism**

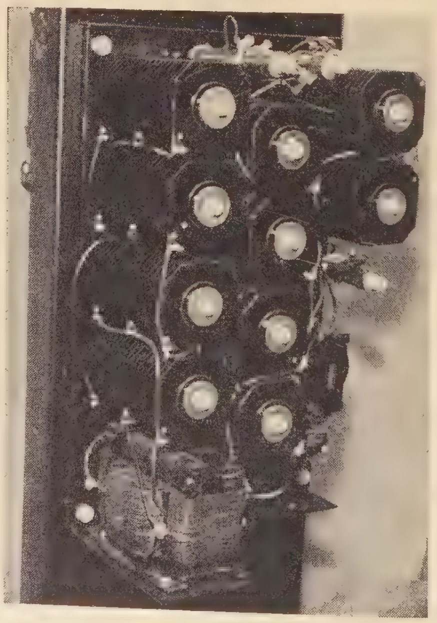


**Figure 6. Voltage regulator for a-c generator**

### Voltage Regulators for A-C Generators

It has long been recognized that a-c generators inherently have a poor regulation, lacking the advantage of a series field for maintaining a nearly constant voltage under varying loads. The device shown in figure 6 was developed to meet the demand for a simple voltage regulator, with no moving parts, for small-size a-c generators. It consists of copper-oxide rectifier units assembled with the proper transformers, reactors, and resistors to provide an increase in the exciter shunt-field current proportional to the increase in voltage required under varying loads on the generator. As indicated in figure 7, changes in generator load are reflected in two full-wave rectifier units. Rectifier I is energized by a current transformer, and is adjusted to produce a compounding effect to some voltage less than normal at full load. Rectifier II, energized from the generator potential, supplies the additional rectified field current necessary for maintaining normal generated voltage. A small change from normal potential on the circuits of rectifiers III and IV causes a relatively large change in the output of the three-core reactor in series with rectifier II.

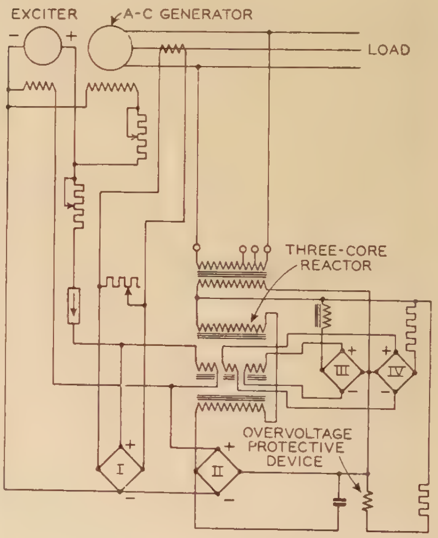


**Figure 7. Voltageregulator**

Under normal conditions of operation, this type of regulator will maintain the voltage within plus or minus three per cent from no load to full load.

Another simple form of a-c regulator is shown in figure 8, this requiring special design of the generator and exciter fields

### RECTIFIERS FOR THE PREVENTION OF ELECTROLYSIS

Corrosion of underground structures can be mitigated by the use of cathodic protection, and is conveniently accomplished by connecting the underground structure to the negative terminal of a d-c source and by maintaining it negative to the earth by 0.3 volt or greater. Corrosion occurs in underground structures due to stray currents from d-c systems, and from electrochemical reactions between the structure and the surrounding soil. Small currents flow from the underground structure through the soil to other parts of the structure, corrosion occurring where the currents leave the structure. Figure 9 shows an outdoor installation of a rectifier unit rated 30 amperes at ten volts, used to protect a section of a pipe line from corrosion. The use of the copper-oxide rectifier for this d-c supply is preferred to other d-c sources, because of its efficiency at low voltage and the fact that a minimum of maintenance is required, such as an occasional check of the output to adjust for seasonal variations in the soil. The device is noiseless and free from radio interference, factors which are important when the device must be located in residential districts. The schematic diagram in figure 10 indicates how this type of device is connected to protect a section of pipe against corrosion.

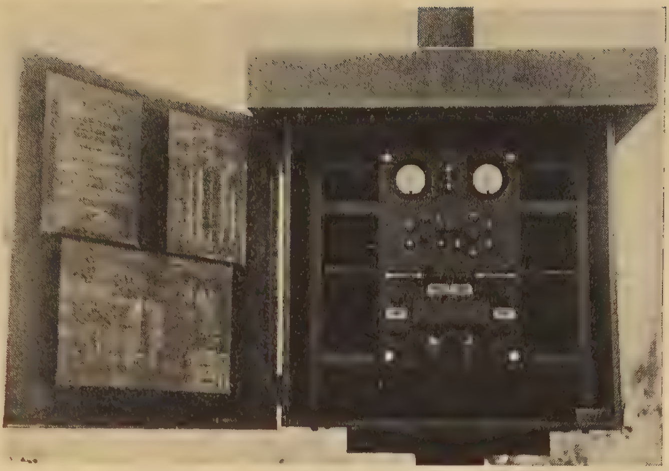


**Figure 9.** Installation of rectifier for protection against electrolysis on pipe line

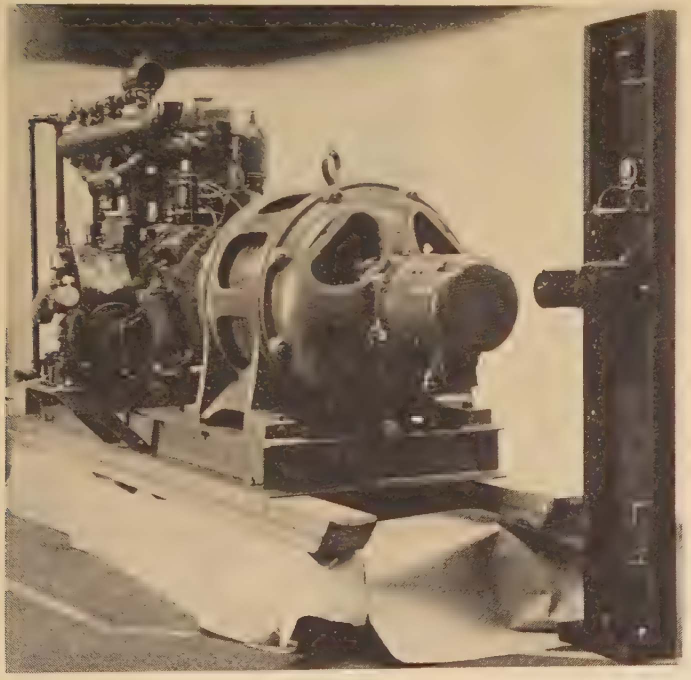


**Figure 8.** The rectifiers on this switchboard provide voltage regulation for the large engine-driven a-c generator

## III. Valves in Control Circuits

The asymmetric resistance characteristics of this rectifier makes it particularly suitable as a valve to control the path of flow of direct current. This type of application has increased the versatility of control circuits and has reduced the number of mechanical relays necessary to complete many control functions. This is best illustrated by a few of the examples given in figure 11.

Remote control of many devices may be accomplished in a minimum time by the system of polarized lines, shown for two wires in figure 11*A*. Relay *A* or *B* will operate depending on the relative polarities of the bus to which they are connected. This simple two-conductor system may be arranged to operate over one conductor and a good ground return such as a water pipe, which is sometimes convenient in the remote control of pumping plants. By the use of three or more wires the number of relays that can be operated increases[5] because of the many possible combinations of polarized lines.

The rectifier valve has become quite useful in isolating the flow of direct current within parts of a circuit, as shown in figure 11*B*. This shows a system of relays and rectifier valves, each of which may be energized either from a common test bus or through contacts on alarm devices. Each alarm contact allows but one relay to operate, the valve in that circuit preventing current flow to the test bus and to other relays. The circuit, and all signal lamps, may be checked conveniently by depressing the test button, wherein all of the relays are energized simultaneously. Figure 12 illustrates a group of rectifier valves and relays used

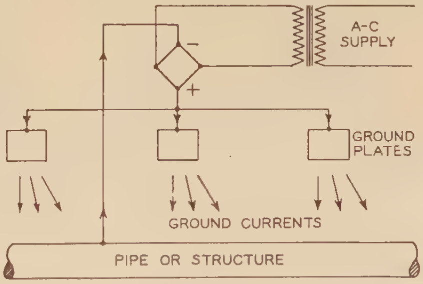
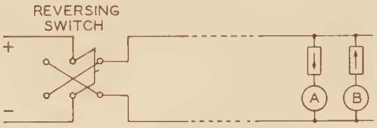
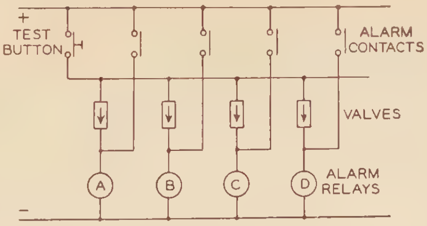


**Figure 10.** Cathodic protection against electrolysis



(a) — SELECTIVE OPERATION OF RELAYS OVER POLARIZED LINES



(b) — VALVES FOR ISOLATION OF ALARM CIRCUITS

**Figure 11**

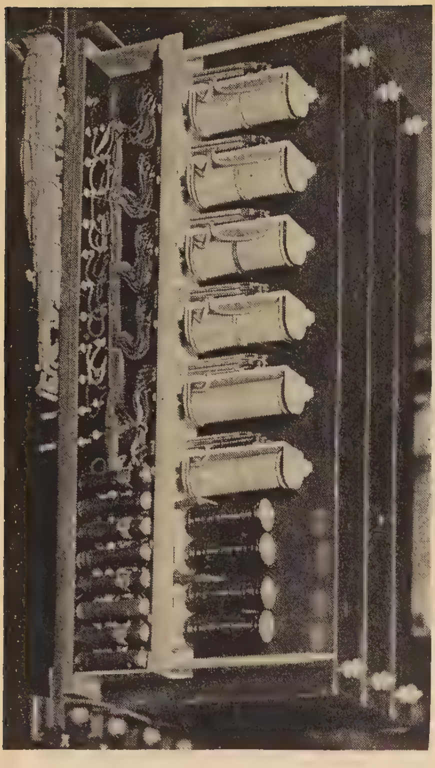


Figure 12. Valve-type rectifiers installed in annunciator circuits (cover removed from one group only)

in the alarm signaling circuits of a large hydroelectric generating plant. This group of 16 rectifiers is sufficient to include all alarm devices, such as may be actuated by bearing, coil, and core temperatures, for one generator.

## IV. Plate-Type Rectifiers

During the first ten years of copper-oxide-rectifier manufacture, contact with the oxide surface was obtained by means of soft metal washers. The rectifier disks were assembled in the proper direction on bolts with the necessary cooling fins and spacers. A special cupped spring washer on each bolt was tightened to obtain high contact pressure between the soft metal washers and the oxide surfaces. The size of disks was limited to a diameter of $1^{1}/_{2}$ inches by the ability to maintain uniform pressure over the entire surface.

Continued research during that time developed a satisfactory method of spraying a conducting coating on large copper-oxide plates.[6] The necessity for high contact pressure having been removed, the new rectifier plates with sprayed coating are assembled a fraction of an inch apart and the losses are dissipated by means of forced air. Electrical connections between plates are made with clips. Four sizes of plates, 10 inches and 12 inches in length, and 3 inches and $4^{3}/_{8}$ inches in width, have been used in group assemblies. The rating in output of a three- by ten-inch plate assembled in a properly ventilated, three-phase rectifier, is 20 watts at six volts d-c maximum. A complete three-phase full-wave rectifier which would require six plates, would then have an output rating of 120 watts at six volts, or 20 amperes, six volts d-c maximum. In the larger plates current capacity increases in proportion to the area, but the voltage rating remains the same. The plates can of course be connected in series or parallel, to any desired capacity. The development of the plate-type copper-oxide rectifier will not supplant, but will supplement, the standard design disk assemblies, and will increase the number of applications in the high-current low-voltage field.

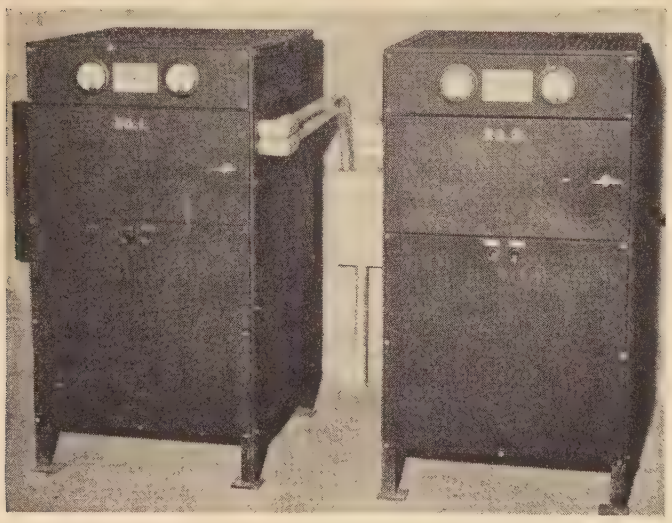


Figure 13. Plate-type rectifiers installed in film laboratory for stripping silver from film

The major field for such units, is in the electrochemical industry, including, for example, chemical processing, electrolytic cleaning, and electroplating. Figure 13 shows an installation of two plate-type rectifiers each rated four volts, 200 amperes d-c output at 220 volts, three-phase, 60 cycles, a-c input. These are installed in a laboratory for use in stripping silver from salvaged film. Figure 14 shows a large-capacity plate-type rectifier. This rectifier has an output rating of 1,500 amperes, six volts maximum for 220 volts, three-phase, 60 cycles, a-c input.

## Conclusions

No attempt has been made herein to list all possible applications, but to describe a few representative types and to show installation photographs of rectifiers in new kinds of services. Units have been assembled with ratings which vary from 0.001 watt to several kilowatts in capacity. This is a device which finds applications in any field, whether it be transportation, power, or industry. The future should see increased application for simplifying control and metering problems.

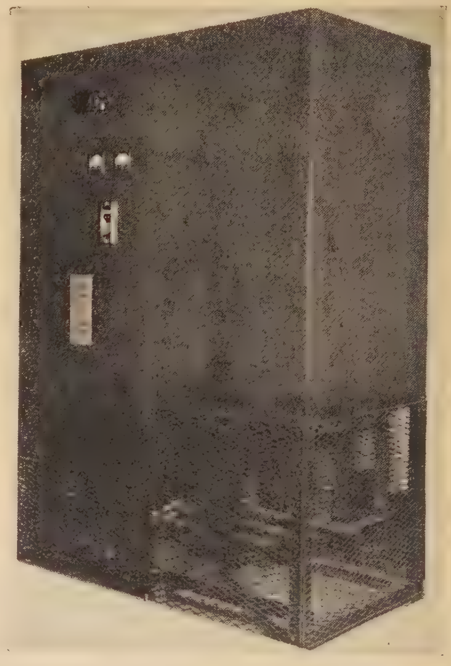


Figure 14. Plate-type rectifier, 1,500 amperes, 6 volts d-c output, built for electroplating service

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# The Electrostatic Unbalance of Transmission Lines and Its Effect on the Application of Petersen Coils

By JOHN ALEXANDER MELVIN LYON
ASSOCIATE AIEE

RECENTLY three Petersen coils were installed on the 66-kv transmission system of the Metropolitan Edison Company of Pennsylvania. These Petersen coils provide service protection to approximately 320 miles of overhead transmission lines against outages and voltage dips which would otherwise result when single phase-to-ground flashovers occur on the system. Much of the 66-kv transmission system consists of two-circuit lines with vertical configurations of the line conductors with no transpositions prior to the Petersen-coil installation.

During the tuning tests on these Petersen coils which were made before putting them in service, it was found that excessive currents were flowing through the coils when tuned with the system, even though there was no ground fault on the system. These currents far exceeded the continuous current ratings of the coils, and they were of such magnitude that the system neutral in some cases shifted as much as 70 per cent above ground. The shift in the neutral above ground, if allowed to remain on the system, would have needlessly subjected the line insulation and connected apparatus to dynamic overvoltages. Accordingly, an investigation was made to determine the cause of this excessive current.

Measurements obtained of the line-to-ground voltages with the system neutral isolated revealed an abnormally unbalanced capacity to ground. That is, the capacities to ground of the three phases were unequal, causing unequal voltages and, therefore, with the Petersen coils in the neutral, excessive current flowed. The unbalanced capacity was accounted for by the lack of transpositions in the transmission lines. It became apparent that by rearranging some of the circuits, the direct capacities of the three phases to ground could be balanced and the circulating current passing through the Petersen coils would be reduced to a small fraction of its original value.

This paper deals with the analysis of zero-sequence electrostatic unbalance of transmission lines to neutral, illustrates the methods of calculation, applies these calculations to obtain a proper balance in the most economical manner, and presents experimental data which verify the methods and procedure used for the solution of the problem. The subject of electrostatics is considered not in its entirety, but only to the extent necessary for the application of impedors (also grounding transformers and neutral reactors). It is hoped that the information embodied in this paper may be of use to others contemplating the use of Petersen coils, neutral reactors, or grounding transformers. The material which follows should not be construed as an attempt to add to the subject of electrostatics; it is instead the application of well-known fundamentals to a very practical situation. For this reason there is at the conclusion of the text a list of general references which contain all of the necessary theory and methods which are used herein.

Briefly, a Petersen coil is an iron-core variable inductance which, when system leg voltage is applied across it, passes a current the magnitude of which is equal to the charging current in a line-to-ground fault on the system when the system neutral is isolated. During the occurrence of a single line-to-ground fault, the Petersen coil causes the flow of a reactive current which is equal to and 180 degrees out of phase with the capacitive current which flows in the ground fault. The result is that the current in the arc is reduced to very nearly zero, the arc is extinguished, and the temporary ground fault disappears without having become a permanent ground fault or having developed into a line-to-line fault as is so often the case. The coil operation does not compensate for the small amount of in-phase or loss current which is usually present in the arc. In practice the current from these two sources is small and not sufficient to maintain the arc. Owing to the fact that a perfect electrostatic balance cannot be obtained practically, it is to be expected that some current will flow through the coil with system normal. This has been the case in previous installations. This flow of current does not interfere with the functioning of the coil in arc extinction in any practical case; the main objection to it, if it exists to an abnormal degree, is that of neutral displacement.

Figure 1 shows the schematic diagram of an impedor applied to a transmission line. The capacitance values of the line are shown as lumped constants in this diagram, and zero-sequence capacitance will be considered in this manner throughout the discussion. This can be done with impunity because in the application of impedors one is concerned primarily with the parallel circuit constants of the lines; the series reactance and resistance of the transmission lines are neglected in the analysis which follows. In the case of an actual transmission system, there will be a coil placed in the neutral of every ground bank, or a coil may serve a group of two or more ground banks. In some instances it may be desirable to separate a ground bank from ground completely and thereby save the cost of an additional coil. Of course, a Petersen-coil-protected system must be electrically insulated by transformers from every other system which is either grounded or ungrounded.

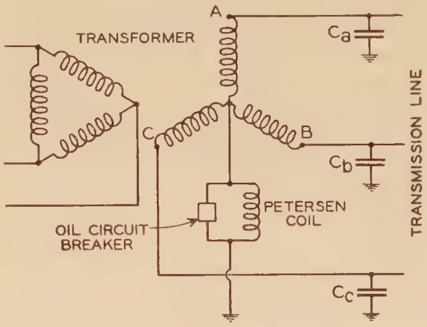

**Figure 1. A Petersen coil applied to a transmission line**

On the Metropolitan Edison Company system a coil was used at each of the three grounding banks which were originally chosen for number and positions according to relaying and switching requirements. It is desirable, when a system is operating in sections, that each section should be able to operate alone

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with Petersen-coil protection. The analysis loses none of its generality through the consideration of only one coil, and the reader is referred to the general theory on coil operation found in the list of references on that subject.

Now the installation of a coil upon a transmission system requires that the coil be tuned for the transmission lines which it is to protect; the coil must be tuned and set at a different tap when additional miles of line are added to the number which it must protect, or when the number of miles which it protects is reduced, such as in switching operations. This tuning process, varying the inductance by means of taps, corresponds to obtaining the resonance point for a simple series circuit. The tuning is accomplished while the transmission lines are operating under normal conditions without the presence of a ground fault. This is one of the several possible methods of tuning. For a given length of line, the tuned point is found when the tap setting, which corresponds to the maximum residual ground current, is obtained.

Figure 2 illustrates the electrical circuit. One tunes, of course, the zero-sequence circuit of figure 2. Figure 3 shows the comparable simple series circuit. It is such a circuit as this that is tuned to resonance.

It can be seen that even with a solidly grounded system the grounding bank helps to tune this zero-sequence circuit and if $E_0$, the zero-sequence voltage, is large, it appears that a large ground current would result.

Referring to figure 3, consider the coil short circuited, or in other words, the system is to be solidly grounded

Let

$I_0$ = zero-sequence component of phase current

$I_n$ = current through neutral of ground bank

$X_t$ = zero-sequence reactance of transformer

$X_{\text{cap.}}$ = average line-to-neutral zero-sequence capacitive reactance

$R_g$ = equivalent ground resistance for entire circuit

$X_{c1}$ = zero-sequence reactance of coil

Then:

$$I_n = 3I_0 = 3\frac{E_0}{3R_g + jX_t - jX_{\text{cap.}}}$$

Even when solidly grounded, the ground banks of the Metropolitan Edison Company had heavy ground currents. The reason for this was a large $E_0$ which was caused by the electrostatic or capacitive unbalance of the three lines to ground.

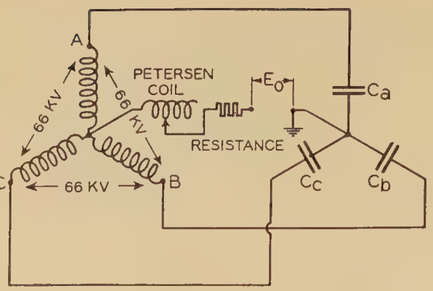

Figure 2. The three-phase circuit of a Petersen-coil installation

Now when the impedor is in the neutral of the ground bank, the current becomes:

$$I_n = 3I_0 = 3\frac{E_0}{3R_g + jX_t + jX_{c1} - jX_{\text{cap.}}}$$

The coil is in tune for the transmission system when $X_{c1}$ is of such value that

$$X_t + X_{c1} = X_{\text{cap.}}$$

and this leaves the resistance $R_g$ as the only factor limiting the current for a given voltage.

In tuning on the Metropolitan Edison system, the residual ground current increased on the resonance peak to as much as five times the continuous current rating of the Petersen coil. Obviously, the coils could not be put in service under such conditions.

In the haste to place the coils into operation during the lightning season, a futile attempt was made to achieve electrostatic balance by interchanging the top and bottom phases of a section of vertically spaced line. It is shown in the analysis to follow that for vertical construction, the top and bottom wires have higher capacitances than the middle wire which was left unchanged. In all of the work the effect of grounded crossarms and poles was neglected.

Vertical construction is used predominately on the lines of the Metropolitan Edison Company, although it has been found that all of the other types of construction, double and single lines, resulted in capacitive unbalance which was appreciable. The system under consideration was almost completely untransposed and this led, of course, to the resultant state of unbalance.

There follows the analysis applied to a typical transmission line as shown in figure 4.

Let

$r$ = radius of conductors in inches

$Q_a$, $Q_b$, etc. = charge on conductors $A$, $B$, etc., in statcoulombs per centimeter

$E_a$, $E_b$, etc. = voltage above ground of conductors $A$, $B$, etc.

$C_a$, $C_b$, etc. = capacity of respective conductors to ground

Then using the method of images (Attwood, "Electric and Magnetic Fields," page 113) one obtains the following:

$$E_a = 2\left(Q_a \log_\epsilon \frac{2ag}{r} + Q_b \log_\epsilon \frac{ab'}{ab} + Q_c \log_\epsilon \frac{ca'}{ca}\right) \tag{1}$$

$$E_b = 2\left(Q_a \log_\epsilon \frac{ab'}{ab} + Q_b \log_\epsilon \frac{2bg}{r} + Q_c \log_\epsilon \frac{ca'}{ca}\right) \tag{2}$$

$$E_c = 2\left(Q_a \log_\epsilon \frac{ca'}{ca} + Q_b \log_\epsilon \frac{bc'}{bc} + Q_c \log_\epsilon \frac{2cg}{r}\right) \tag{3}$$

Similar equations may be written for any number of conductors. Now in general:

$$C\ (\text{Capacity}) = \frac{Q\ (\text{Charge})}{E\ (\text{Voltage})} \tag{4}$$

The direct or zero-sequence capacitance of a conductor $A$ to ground is the ratio of the charge on conductor $A$ to its potential (the zero-sequence potential) when all other conductors except the reference conductor, in this case the ground, are at the potential (zero-sequence potential) of $A$. Solving equations 1 to 3 would give equations for $Q_a$, $Q_b$, and $Q_c$ in terms of $V_a$, $V_b$, and $V_c$. The three wires are allowed to assume the same potential with respect to ground; that is, $V_a = V_b = V_c$. It is thus possible to solve by the method of determinants equations 1, 2, and 3 for $Q_a$, and by dividing through by $V_a$, according to equation 4, the coefficients $V_a$, $V_b$, and $V_c$ are removed from the expression which now represents the capacitance, $C_a$.

$$C_a = \frac{\begin{vmatrix} 1 & 2\log_\epsilon \frac{ab'}{ab} & 2\log_\epsilon \frac{ca'}{ca} \\ 1 & 2\log_\epsilon \frac{2bg}{r} & 2\log_\epsilon \frac{bc'}{bc} \\ 1 & 2\log_\epsilon \frac{bc'}{bc} & 2\log_\epsilon \frac{2cg}{r} \end{vmatrix}}{\begin{vmatrix} 2\log_\epsilon \frac{2ag}{r} & 2\log_\epsilon \frac{ab'}{ab} & 2\log_\epsilon \frac{ca'}{ca} \\ 2\log_\epsilon \frac{ab'}{ab} & 2\log_\epsilon \frac{2bg}{r} & 2\log_\epsilon \frac{bc'}{bc} \\ 2\log_\epsilon \frac{ca'}{ca} & 2\log_\epsilon \frac{bc'}{bc} & 2\log_\epsilon \frac{2cg}{r} \end{vmatrix}} \text{ statfarads per centimeter} \tag{5}$$

Expressions can likewise be found for $C_b$ and $C_c$.

It is more convenient for computation to use logarithms to the base 10, and to obtain capacitance in microfarads per mile; thus equations 6, 7, and 8 arise.

$$C_a = 0.0389 \times \frac{\begin{vmatrix} 1 & \log\frac{ab'}{ab} & \log\frac{ca'}{ca} \\ 1 & \log\frac{2bg}{r} & \log\frac{bc'}{bc} \\ 1 & \log\frac{bc'}{bc} & \log\frac{2cg}{r} \end{vmatrix}}{\begin{vmatrix} \log\frac{2ag}{r} & \log\frac{ab'}{ab} & \log\frac{ca'}{ca} \\ \log\frac{ab'}{ab} & \log\frac{2bg}{r} & \log\frac{bc'}{bc} \\ \log\frac{ca'}{ca} & \log\frac{bc'}{bc} & \log\frac{2cg}{r} \end{vmatrix}}$$

microfarads per mile (6)

The denominators of 6, 7, and 8 are the same and can be denoted in each case by the symbol $D$.

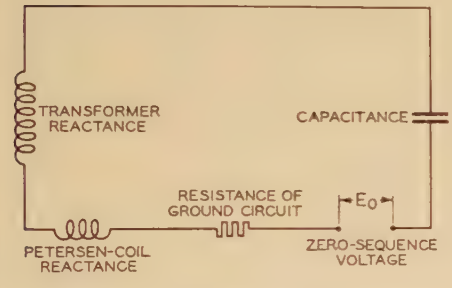

**Figure 3. The equivalent zero-sequence resonant circuit**

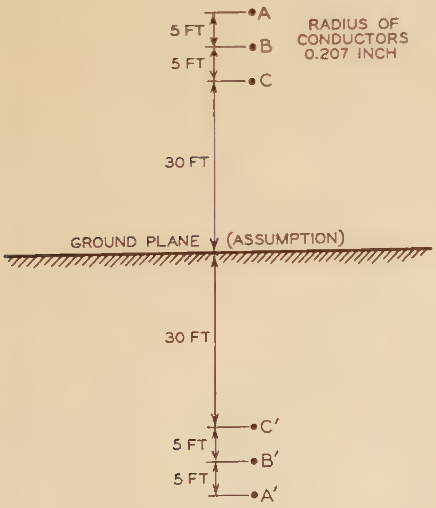

**Figure 4. The transmission line spacings used in the calculations**

$$C_b = 0.0389 \times \frac{\begin{vmatrix} \log\frac{2ag}{r} & 1 & \log\frac{ca'}{ca} \\ \log\frac{ab'}{ab} & 1 & \log\frac{bc'}{bc} \\ \log\frac{ca'}{ca} & 1 & \log\frac{2cg}{r} \end{vmatrix}}{D}$$

microfarads per mile (7)

$$C_c = 0.0389 \times \frac{\begin{vmatrix} \log\frac{2ag}{r} & \log\frac{ab'}{ab} & 1 \\ \log\frac{ab'}{ab} & \log\frac{2bg}{r} & 1 \\ \log\frac{ca'}{ca} & \log\frac{bc'}{bc} & 1 \end{vmatrix}}{D}$$

microfarads per mile (8)

Solving for the capacitances of the line of figure 4:

$$\log\frac{2ag}{r} = \log\frac{12 \times 2 \times 40}{0.207} = 3.666$$

$$\log\frac{2bg}{r} = \log\frac{12 \times 2 \times 35}{0.207} = 3.609$$

$$\log\frac{2cg}{r} = \log\frac{12 \times 2 \times 30}{0.207} = 3.541$$

$$\log\frac{ab'}{ab} = \log\frac{75}{5} = 1.176$$

$$\log\frac{ca'}{ca} = \log\frac{70}{10} = 0.846$$

$$\log\frac{bc'}{bc} = \log\frac{65}{5} = 1.114$$

$$D = \begin{vmatrix} 3.666 & 1.176 & 0.846 \\ 1.176 & 3.609 & 1.114 \\ 0.846 & 1.114 & 3.541 \end{vmatrix} = 37.08$$

$$(C_a \times D) = 0.0389 \times \begin{vmatrix} 1 & 1.176 & 0.846 \\ 1 & 3.609 & 1.114 \\ 1 & 1.114 & 3.541 \end{vmatrix}$$

$$= 0.0389 \times 6.523$$

$$C_a = \frac{(C_a \times D)}{D} = 0.0389 \times \frac{6.523}{37.08}$$

$= 0.00685$ microfarad per mile

$$(C_b \times D) = 0.0389 \times \begin{vmatrix} 3.666 & 1 & 0.846 \\ 1.176 & 1 & 1.114 \\ 0.846 & 1 & 3.541 \end{vmatrix}$$

$$= 0.0389 \times 5.962$$

$$C_b = \frac{(C_b \times D)}{D} = \frac{0.0389 \times 5.962}{37.08}$$

$= 0.00625$ microfarad per mile

$$(C_c \times D) = 0.0389 \times \begin{vmatrix} 3.666 & 1.176 & 1 \\ 1.176 & 3.609 & 1 \\ 0.846 & 1.114 & 1 \end{vmatrix}$$

$$= 0.0389 \times 7.028$$

$$C_c = \frac{(C_c \times D)}{D} = \frac{0.0389 \times 7.028}{37.08}$$

$= 0.00737$ microfarad per mile

It is the problem now to show that such an electrostatic unbalance to neutral as indicated by the zero-sequence capacitance values above can produce a large $E_0$, or zero-sequence voltage, which is responsible for the large residual currents. In this computation, it makes no difference whether one considers one mile or 100 miles of line having the per mile capacitance values which have just been found.

Therefore:

$$X_a = \frac{-j}{2\pi f C_a} = \frac{-j}{377 \times 0.00685 \times 10^{-6}}$$
$$= -j387{,}000 \text{ ohms}$$

NOTE: The letter $f$ designates frequency in the above expression

$$X_b = \frac{-j}{2\pi f C_b} = \frac{-j}{377 \times 0.00625 \times 10^{-6}}$$
$$= -j424{,}000 \text{ ohms}$$

$$X_c = \frac{-j}{2\pi f C_c} = \frac{-j}{377 \times 0.00737 \times 10^{-6}}$$
$$= -j360{,}000 \text{ ohms}$$

Now these zero-sequence capacitive reactances are considered as forming an unsymmetrical wye load with balanced line-to-line voltages of 66,000 volts. The method of symmetrical components with the usual notation is used.

$$X_0 = 1/3\ (X_a + X_b + X_c)$$
$$= \frac{-j}{3}\ (387{,}000 + 424{,}000 + 360{,}000) \text{ ohms}$$
$$= -j390{,}000 \text{ ohms} = -j390 \times 1{,}000 \text{ ohms}$$

$$X_1 = 1/3\ (X_a + aX_b + a^2X_c)$$
$$= 1/3\{-j387{,}000 - j424{,}000\ (-0.5 + j0.866) - j360{,}000\ (-0.5 - j0.866)\} \text{ ohms}$$
$$= (18.3 + j2) \times 1{,}000 \text{ ohms}$$

$$X_2 = 1/3\ (X_a + a^2X_b + aX_c)$$
$$= 1/3\{(-j387{,}000 - j424{,}000\ (-0.5 + j0.866) - j360{,}000\ (-0.5 - j0.866)\} \text{ ohms}$$
$$= (-18.3 + j2) \times 1{,}000 \text{ ohms}$$

Now

$$E_0 = I_1X_2 + I_2X_1 \tag{9}$$

$$E_1 = I_1X_0 + I_2X_2 \tag{10}$$

$$E_2 = I_2X_0 + I_1X_1 \tag{11}$$

$$E_1 = \frac{66{,}000}{\sqrt{3}} = 38{,}100 \text{ volts (phase voltage effective value)}$$

$$E_2 = 0 \text{ (not generated)}$$

Using equation 10 there results:

$$38{,}100 = I_1\,(-j390{,}000) + I_2\,(-18.3 + j2) \times 1000$$

or

$$38.1 = I_1\,(-j390) + I_2\,(-18.3 + j2) \tag{12}$$

Using equation 11

$$0 = I_2(-j390{,}000) + I_1(18.3 + j2) \times 1{,}000$$

$$0 = I_2\,(-j390) + I_1\,(18.3 + j2) \qquad \textbf{(13)}$$

Remembering that $I_1$ and $I_2$ are vectors, one can obtain four linear simultaneous algebraic equations from (12) and (13), and these can be solved for $I_1$ and $I_2$ which are found to be:

$$I_1 = 0.000735 + j0.0979$$

$$I_2 = 0.00459 - j0.000735$$

Substituting these values in (9), it follows:

$$V_0 = (0.000735 + j0.0979)(-18.3 + j2) \times 1000 + (0.00459 - j0.000502) \times (18.3 + j2) \times 1000$$

$$V_0 = -125.25 - j1799.1$$

Absolute value of $V_0$ = 1,800 volts (effective value) **(14)**

In an actual test at the West Reading plant of the Metropolitan Edison Company it was found that 57 miles of line having the dimensions and construction which have just been considered operated with a zero-sequence voltage or neutral displacement voltage of 1,920 volts. This checks very closely with the value of 1,800 volts from the computations; it should be obvious that any discrepancy which is present can be attributed to the sag in the lines and other immeasurable irregularities in the lines. Furthermore, the computations have involved the assumption of the plane of zero potential or ground plane.

Transpositions were made at the regular switching stations or accessible H-frame structures of the above system for the 57 miles considered and as a result the displacement voltage was reduced to 144 volts. With this voltage even under conditions of resonance the Petersen coils could operate safely within their continuous ratings.

It should be pointed out that zero-sequence electrostatic balance to neutral can be and was obtained in actual practice, both by completely transposing as well as by interchanging two of the three line wires.

Refer to figure 4.

$C_a$ = 0.00685 microfarad per mile
$C_b$ = 0.00625 microfarad per mile
$C_c$ = 0.00737 microfarad per mile

The arithmetical mean of $C_b$ and $C_c$ is 0.00681 microfarad per mile. Thus it can be seen that if $A$ phase is always on top, $B$ phase is half of the distance in the middle and the other half of this distance on the bottom, and $C$ phase is half of the distance on the bottom and the other half of the distance in the middle position, an almost perfect balance of capacities to neutral is obtained.

Economic considerations were important in the revision of the existing transmission lines of the Metropolitan Edison Company. Transpositions were confined to switching stations or other accessible points such as H-frame locations; no new structures were erected. In some instances one line was arranged so as to electrostatically balance a second line, although an outage of either line would cause the line remaining in service to throw some unbalance on the system. There are several instances on the system of balancing one line against one or more lines. However, the system is large enough so that two or three line outages may occur without causing a prohibitive residual current, assuming, of course, that the coils have been retuned for the new system setup. In some very remote conditions of operation, the coils will have to be detuned or else taken out of service completely by short-circuiting them, which is equivalent to solidly grounding the transformer banks.

It seems necessary to add that in some instances the capacitances of the line insulators will be an important factor in the electrostatic unbalance to neutral. The capacitance of an individual pin-type insulator may be as high as 60 micro-microfarads. With bonded and grounded hardware the added balanced capacitance of the insulators could conceivably reduce the displacement voltage by ten per cent.

Obviously, the method of obtaining the direct capacitances to neutral of the line conductors can be extended to apply for transmission lines having one or more ground wires; double lines with or without ground wires yield also to this method. The equations for capacitances of double transmission lines with two ground wires are given in the appendix. Calculations involving all of these possibilities were made for the Metropolitan Edison Company system and the results were checked in the field; an accuracy was obtained in all cases comparable to the case which has just been considered in detail.

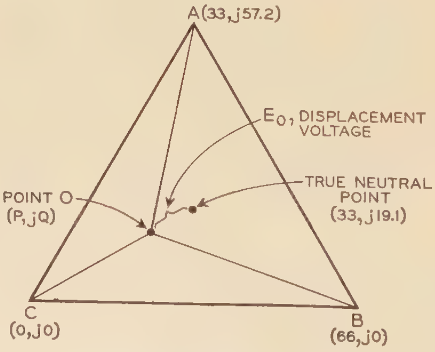

Figure 5. Potential diagram which applies to the method of the appendix

## Appendix

The following alternative method is given for obtaining the displacement voltage $E_0$. It is especially useful for those who are unfamiliar with the symmetrical-component notation.

Figure 5 shows the potential diagram for three equal line voltages drawn in the complex domain. The line-to-line voltage is 66,000 volts. The co-ordinates in figure 5 are given in thousands of volts.

Let

$E_{ao}$, $E_{bo}$, and $E_{co}$ = the voltages from $O$ to $A$, $B$, and $C$, respectively, expressed in thousands of volts

As before

$$X_a = -j387{,}000 \text{ ohms}$$

$$X_b = -j424{,}000 \text{ ohms}$$

$$X_c = -j360{,}000 \text{ ohms}$$

Now

$$E_{ao} = 33 - P + j57.2 - jQ$$

$$E_{bo} = 66 - P + j0 - jQ$$

$$E_{co} = 0 - P + j0 - jQ$$

The above equations express the line-to-neutral voltages in terms of the co-ordinates of the complex number system.

If it is assumed that the direction of the line currents $I_a$, $I_b$, and $I_c$ is such that they all flow toward the neutral point $O$, then:

$$I_a + I_b + I_c = 0 \qquad \textbf{(15)}$$

Now

$$I_a = \frac{E_{ao}}{X_a}$$

$$I_b = \frac{E_{bo}}{X_b}$$

$$I_c = \frac{E_{co}}{X_c}$$

These three currents will be in amperes if $X_a$, $X_b$, and $X_c$ are in thousands of ohms, for the voltages are expressed in thousands of volts.

$$I_a = \frac{33 - P + j57.2 - jQ}{-j387} = j0.0852 - j0.00258P - 0.1475 + 0.00258Q \qquad \textbf{(16)}$$

$$I_b = \frac{66 - P - jQ}{-j424} = j0.1557 - j0.00236P + 0.00236Q \qquad \textbf{(17)}$$

$$I_c = \frac{-P - jQ}{-j360} = -j0.00278P + 0.00278Q \qquad \textbf{(18)}$$

Then substituting the values of the currents from equations 16, 17, and 18 in equation 15 there is produced (19).

$$j0.0852 - j0.00258P - 0.1475 + 0.00258Q + j0.1557 - j0.00236P + 0.00236Q - j0.00278P + 0.00278Q = 0 \qquad \textbf{(19)}$$

Now the algebraic sum of the terms directed along the axis of reals may be equated to zero.

$$-0.1475 + 0.00258Q + 0.00236Q + 0.00278Q = 0 \qquad (20)$$

$$0.00772Q = 0.1475$$

$$Q = 19.1$$

Similarly the algebraic sum of the terms directed along the axis of imaginaries may be equated to zero.

$$j0.0852 - j0.00258P + j0.1557 - j0.00236P - j0.00278P = 0 \quad (21)$$

$$0.00772P = 0.2409$$

$$P = 31.2$$

From figure 5 the co-ordinates of the true neutral are 33, $j19.1$. Now $E_0$ is the zero-sequence voltage or the displacement voltage from true neutral.

$$\begin{aligned} E_0 &= \sqrt{(19.1 - Q)^2 + (33 - P)^2} \\ &= \sqrt{(19.1 - 19.1)^2 + (33 - 31.2)^2} \\ &= 1.8 \text{ thousands of volts} \\ E_0 &= 1{,}800 \text{ volts} \qquad (22) \end{aligned}$$

This value of the residual voltage agrees with the value obtained by the first method.

The direct capacitances for a double-circuit transmission line with two ground wires can be found by writing equations similar to (1), (2), and (3) and proceeding as for the single-circuit three-wire line. Let $A$, $B$, and $C$ represent the conductors for one circuit; $D$, $E$, and $F$ will represent the conductors for a second circuit; $M$ and $N$ will represent two ground wires; and $r_a$, $r_b$, $r_c$, $r_d$, $r_e$, $r_f$, $r_m$, $r_n$ will represent radii of the respective conductors. Then $ag$ will be the distance of conductor $A$ to ground. The expression $ab'$ will represent the distance from $A$ to the image $B'$ of $B$, and $ab$ will represent the distance from $A$ to $B$. The same system will apply to all conductor distances.

There follows a list of terms which must be computed. The logarithms are to be taken using the base 10.

$$C_a = 0.0389 \times \frac{\begin{vmatrix} 1 & P_{ab} & P_{ac} & P_{ad} & P_{ae} & P_{af} & P_{am} & P_{an} \\ 1 & P_{bb} & P_{bc} & P_{bd} & P_{be} & P_{bf} & P_{bm} & P_{bn} \\ 1 & P_{bc} & P_{cc} & P_{cd} & P_{ce} & P_{cf} & P_{cm} & P_{cn} \\ 1 & P_{bd} & P_{cd} & P_{dd} & P_{de} & P_{df} & P_{dm} & P_{dn} \\ 1 & P_{be} & P_{ce} & P_{de} & P_{ee} & P_{ef} & P_{em} & P_{en} \\ 1 & P_{bf} & P_{cf} & P_{df} & P_{ef} & P_{ff} & P_{fm} & P_{fn} \\ 0 & P_{bm} & P_{cm} & P_{dm} & P_{em} & P_{fm} & P_{mm} & P_{mn} \\ 0 & P_{bn} & P_{cn} & P_{dn} & P_{en} & P_{fn} & P_{mn} & P_{nn} \end{vmatrix}}{\begin{vmatrix} P_{aa} & P_{ab} & P_{ac} & P_{ad} & P_{ae} & P_{af} & P_{am} & P_{an} \\ P_{ab} & P_{bb} & P_{bc} & P_{bd} & P_{be} & P_{bf} & P_{bm} & P_{bn} \\ P_{ac} & P_{bc} & P_{cc} & P_{cd} & P_{ce} & P_{cf} & P_{cm} & P_{cn} \\ P_{ad} & P_{bd} & P_{cd} & P_{dd} & P_{de} & P_{df} & P_{dm} & P_{dn} \\ P_{ae} & P_{be} & P_{ce} & P_{de} & P_{ee} & P_{ef} & P_{em} & P_{en} \\ P_{af} & P_{bf} & P_{cf} & P_{df} & P_{ef} & P_{ff} & P_{fm} & P_{fn} \\ P_{am} & P_{bm} & P_{cm} & P_{dm} & P_{em} & P_{fm} & P_{mm} & P_{mn} \\ P_{an} & P_{bn} & P_{cn} & P_{dn} & P_{en} & P_{fn} & P_{mn} & P_{nn} \end{vmatrix}} \text{ microfarads per mile} \qquad (23)$$

$$C_b = 0.0389 \times \frac{\begin{vmatrix} P_{aa} & 1 & P_{ac} & P_{ad} & P_{ae} & P_{af} & P_{am} & P_{an} \\ P_{ab} & 1 & P_{bc} & P_{bd} & P_{be} & P_{bf} & P_{bm} & P_{bn} \\ P_{ac} & 1 & P_{cc} & P_{cd} & P_{ce} & P_{cf} & P_{cm} & P_{cn} \\ P_{ad} & 1 & P_{cd} & P_{dd} & P_{de} & P_{df} & P_{dm} & P_{dn} \\ P_{ae} & 1 & P_{ce} & P_{de} & P_{ee} & P_{ef} & P_{em} & P_{en} \\ P_{af} & 1 & P_{cf} & P_{df} & P_{ef} & P_{ff} & P_{fm} & P_{fn} \\ P_{am} & 0 & P_{cm} & P_{dm} & P_{em} & P_{fm} & P_{mm} & P_{mn} \\ P_{an} & 0 & P_{cn} & P_{dn} & P_{en} & P_{fn} & P_{mn} & P_{nn} \end{vmatrix}}{T} \text{ microfarads per mile} \qquad (24)$$

$$C_a = 0.0389 \times \frac{\begin{vmatrix} 1 & P_{ab} + P_{ae} & P_{ac} + P_{ab} & P_{am} + P_{an} \\ 1 & P_{bb} + P_{be} & P_{bc} + P_{bf} & P_{bm} + P_{bn} \\ 1 & P_{bc} + P_{ce} & P_{cc} + P_{cf} & P_{cm} + P_{cn} \\ 0 & P_{bm} + P_{em} & P_{cm} + P_{fm} & P_{mm} + P_{mn} \end{vmatrix}}{\begin{vmatrix} P_{aa} + P_{ad} & P_{ab} + P_{ae} & P_{ac} + P_{ab} & P_{am} + P_{an} \\ P_{ab} + P_{bd} & P_{bb} + P_{be} & P_{bc} + P_{bf} & P_{bm} + P_{bn} \\ P_{ac} + P_{cd} & P_{bc} + P_{ce} & P_{cc} + P_{cf} & P_{cm} + P_{cn} \\ P_{am} + P_{dm} & P_{bm} + P_{em} & P_{cm} + P_{fm} & P_{mm} + P_{mn} \end{vmatrix}} \text{ microfarads per mile} \qquad (25)$$

$$P_{aa} = \log \frac{2ag}{r_a}$$

$$P_{ab} = \log \frac{ab'}{ab}$$

$$P_{ac} = \log \frac{ac'}{ac}$$

$$P_{ad} = \log \frac{ad'}{ad}$$

$$P_{ae} = \log \frac{ae'}{ae}$$

$$P_{af} = \log \frac{af'}{af}$$

$$P_{am} = \log \frac{am'}{am}$$

$$P_{an} = \log \frac{an'}{an}$$

$$P_{bb} = \log \frac{2bg}{r_b}$$

$$P_{bc} = \log \frac{bc'}{bc}$$

$$P_{bd} = \log \frac{bd'}{bd}$$

$$P_{be} = \log \frac{be'}{be}$$

$$P_{bf} = \log \frac{bf'}{bf}$$

$$P_{bm} = \log \frac{bm'}{bm}$$

$$P_{bn} = \log \frac{bn'}{bn}$$

$$P_{cc} = \log \frac{2cg}{r_c}$$

$$P_{cd} = \log \frac{cd'}{cd}$$

$$P_{ce} = \log \frac{ce'}{ce}$$

$$P_{cf} = \log \frac{cf'}{cf}$$

$$P_{cm} = \log \frac{cm'}{cm}$$

$$P_{cn} = \log \frac{cn'}{cn}$$

$$P_{dd} = \log \frac{2dg}{r_d}$$

$$P_{de} = \log \frac{de'}{de}$$

$$P_{df} = \log \frac{df'}{df}$$

$$P_{dm} = \log \frac{dm'}{dm}$$

$$P_{dn} = \log \frac{dn'}{dn}$$

$$P_{ee} = \log \frac{2eg}{r_e}$$

$$P_{ef} = \log \frac{ef'}{ef}$$

$$P_{em} = \log \frac{em'}{em}$$

$$P_{en} = \log \frac{en'}{en}$$

$$P_{ff} = \log \frac{2fg}{r_f}$$

$$P_{fm} = \log \frac{fm'}{fm}$$

$$P_{fn} = \log \frac{fn'}{fn}$$

$$P_{mm} = \log \frac{2mg}{r_m}$$

$$P_{mn} = \log \frac{mn'}{mn}$$

$$P_{nn} = \log \frac{2ng}{r_n}$$

Equation 23 gives the value of the capacitance of conductor $A$. Equation 24, which has the same denominator $T$ as equation 23, gives the value of the capacitance of conductor $B$. If the column of six one's and two zero's successively replaces in the numerator the $A$ column (farthest left), and the $B$, $C$, $D$, $E$, $F$, $M$, and $N$ columns, expressions will be obtained for the capacitances of $A$, $B$, $C$, $D$, $E$, $F$, $M$, and $N$ conductors in the order named. Equation 23 has the replacement in the $A$ column; equation 24 in the $B$ column. The same denominator $T$ is used for all of the expressions.

These eighth-order determinants are rather difficult to solve. If the two circuits and ground wires are unsymmetrically placed on the towers, there can be no great simplification, and the eighth-order determinants will have to be solved laboriously by the method of minors to reduce to lower order determinants.

If the two transmission circuits are symmetrically placed on the tower line so that conductors $A$ and $D$, $B$ and $E$, $C$ and $F$ have the same capacitances, and ground wire $M$ has the same position with respect to circuit $ABC$ as $N$ has with circuit $DEF$, then a considerable simplification may be accomplished. Equation 23 may then be reduced (25).

Equations similar to (25) may be written for $C_b$ or $C_e$, and $C_c$ or $C_f$. This is accomplished by successive replacement of columns in the numerator by the 1-1-1-0 column. A fourth-order determinant is, of course, easily reduced to three third-order determinants by the method of minors, and these in turn are readily solved.

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## Discussion

**F. Von Voigtlander** (The Commonwealth and Southern Corporation, Jackson, Mich.): Doctor Lyon's analysis and computation of the electrostatic unbalance of a transmission line nicely illustrate the application of the theory of electrostatics to the practical solution of system capacitance unbalance problems.

It is interesting to note, however, that for single-circuit lines, the solution of the unbalanced voltages can be found very simply and directly for any common configuration by reference to charts 3, 22, and 23 of Engineering Report No. 16 of the Joint Subcommittee of Development and Research of the National Electric Light Association and the Bell Telephone System.

Using the example cited in the paper, from chart 3 of Report No. 16, we find that the highest voltage listed for five-foot vertical spacing is 22 kv. Entering chart 23 with 22 kv and lowest conductor 30 feet from the ground, we find the residual voltage to be 1.8 kv. Multiplying by the ratio of the actual line voltage (66 kv) to the voltage corresponding to the given spacing (22 kv), we find the characteristic residual voltage for the 66-kv line to be 5.4 kv. The zero-sequence voltage is one-third of the residual, so we have 1.8 kv for the neutral displacement which agrees exactly with Mr. Lyon's results for the totally nontransposed line. The effect of transpositions can readily be taken into account by multiplying this unbalanced voltage by the ratio of the equivalent nontransposed length to the total length of the system.

For twin circuits and circuits with ground wires, the results from these charts would have to be modified, but for single circuits without ground wires, they are well within the accuracy required for this type of work.

**J. A. M. Lyon:** The interesting discussion of F. Von Voigtlander tells of an easy method to obtain the residual voltage of a transmission line by means of published charts to which he has made complete reference. There is no denying that the use of such charts is extremely expeditious in obtaining the residual voltage for a simple transmission line composed of a single circuit without a ground wire.

It should be emphasized again that the author chose for the illustration of the method of his paper, the simplest case which occurred on the transmission system involved. It should also be pointed out again that a large portion of the total line mileage is equipped with double-circuit lines; some of these double-circuit lines as well as some of the single-circuit lines have ground wires. The author indicated in his paper a general method which is applicable to all these double- and single-circuit lines with and without ground wires.

Mr. Von Voigtlander grants that his method would not be satisfactory in these more complicated cases, at least not without numerous modifications and extensions of the charts. Such changes in his method would destroy the original simplicity and would thus defeat its purpose.

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# The Pumping System of the Colorado River Aqueduct

By J. M. GAYLORD
FELLOW AIEE

**Synopsis:** This paper describes the power features of the aqueduct being built to supplement the water supply of Southern California. Three hundred thousand kilowatts of power ultimately will be transmitted from Boulder Dam to operate 45 synchronous motors driving centrifugal pumps. High efficiency, long life, and simplicity of design are given precedence over close voltage regulation and the elimination of momentary interruptions.

THE Colorado River Aqueduct, which will double the present water supply of Southern California, is in its sixth year of construction and the initial development, originally estimated to cost \$220,000,000, is approximately 85 per cent completed. This giant water-supply project is being built by The Metropolitan Water District of Southern California, a public corporation composed at this time (August, 1938) of the cities of Anaheim, Beverly Hills, Burbank, Compton, Fullerton, Glendale, Long Beach, Los Angeles, Pasadena, San Marino, Santa Ana, Santa Monica, and Torrance, a total of 13. The District was organized in 1928; bonds were voted in 1931; in September 1932, the Reconstruction Finance Corporation agreed to buy the first bonds; and construction was started in December of the same year. It is expected that water will be delivered through the aqueduct in 1939.

The project is closely linked to Boulder Dam since the 1,100,000 acre-feet of water appropriated by the District out of the flow of the river will be stored by the Government in Lake Mead and 36 per cent of the firm energy developed at Boulder will be used for the operation of pumping plants on the aqueduct. The power and pumping system, comprising five pumping plants and a 230-kv transmission system, will ultimately demand 300,000 kw of power and use $2^1/_4$ billion kilowatt-hours per year, making the project of special interest to the electrical and mechanical engineer.

### The Aqueduct

The aqueduct has its intake on the Colorado River just above the confluence of the Bill Williams River 150 miles below Boulder Dam. The Parker Dam, just below the mouth of the Bill Williams, is now being completed by the United States Bureau of Reclamation using funds furnished by the District, and will raise the water 72 feet above river level creating a reservoir of 717,000 acre-feet capacity from which the aqueduct will draw its supply. From its intake at Parker reservoir the main aqueduct extends 241.7 miles to the terminal reservoir at Cajalco. This distance is covered by 92.1 miles of tunnel, 54.5 miles of cut and cover conduit, 62.8 miles of open-lined canals, 28.7 miles of inverted siphons, 1.2 miles of pump-delivery lines, 1.1 miles of open ditch, and 1.3 miles of passage through reservoirs.

From the Cajalco reservoir, distribution conduits will deliver water to the member cities of the District. Five pumping stations lift the water from Parker reservoir at elevation 450 feet above sea level to 1,807 feet, the highest point on the aqueduct, from which point flow is by gravity to the terminal reservoir at elevation 1,405. The problem from the standpoint of the electrical and mechani-

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1. For all numbered references, see list at end of paper.

cal engineer was to design and build five pumping plants capable of raising 1,500 second-feet of water through a total net lift of 1,617 feet by means of power obtained principally from Boulder Dam. Figure 1 is a general map of the project showing the location of the transmission lines, pumping plants, and related features of the project.

The Intake plant, figure 10, draws its water directly from the Parker reservoir, lifts it 291 feet, and delivers it through the Colorado River tunnel to Gene Wash reservoir. The Gene pumping plant, figure 11, lifts the water 303 feet additional and delivers it through two tunnels to the Copper Basin reservoir. Since both the Colorado River and Copper Basin tunnels operate as pressure conduits, surge tanks are provided at the tops of each lift. The outflow from Copper Basin is regulated by gates operated by supervisory control from Gene pumping plant. From Copper Basin the water flows by gravity 60 miles to the Iron Mountain pumping plant, figure 12, where the third lift, 144 feet, is made. At this plant no natural storage reservoir is available but a regulating forebay reservoir of 100 acre-feet capacity has been

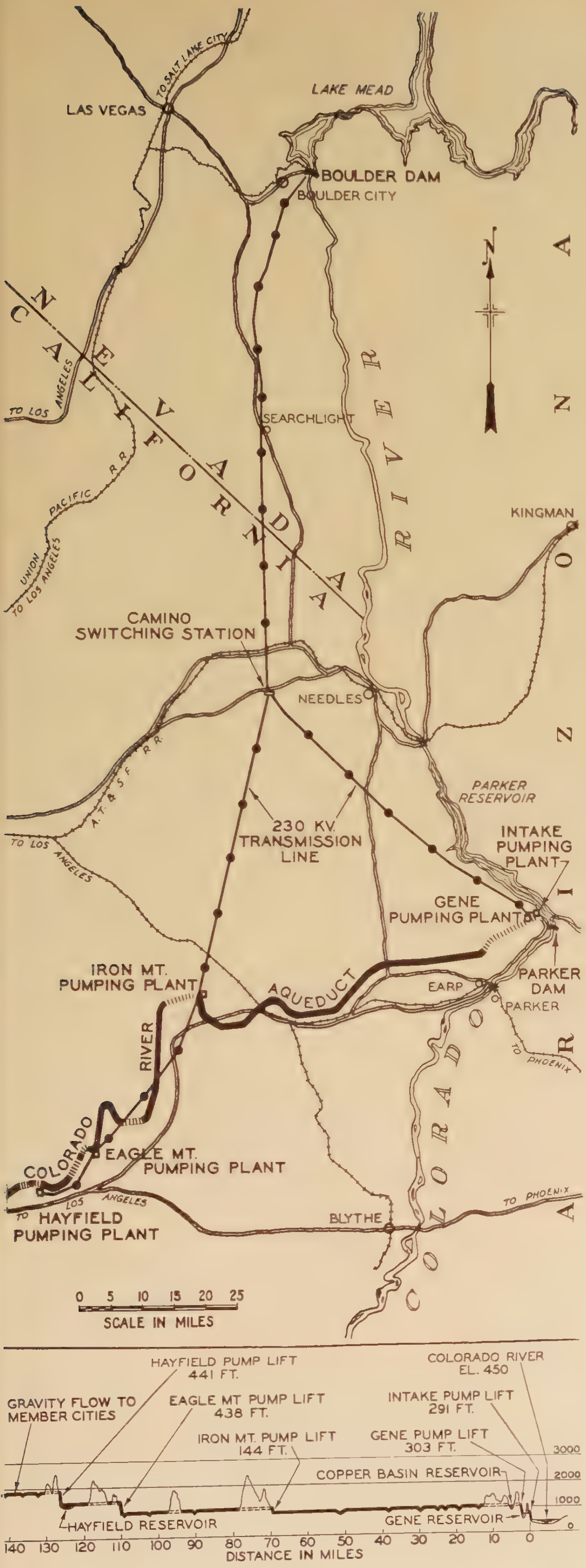


**Figure 1.** Map of power system for Colorado River Aqueduct and profile of section that includes pumping plant

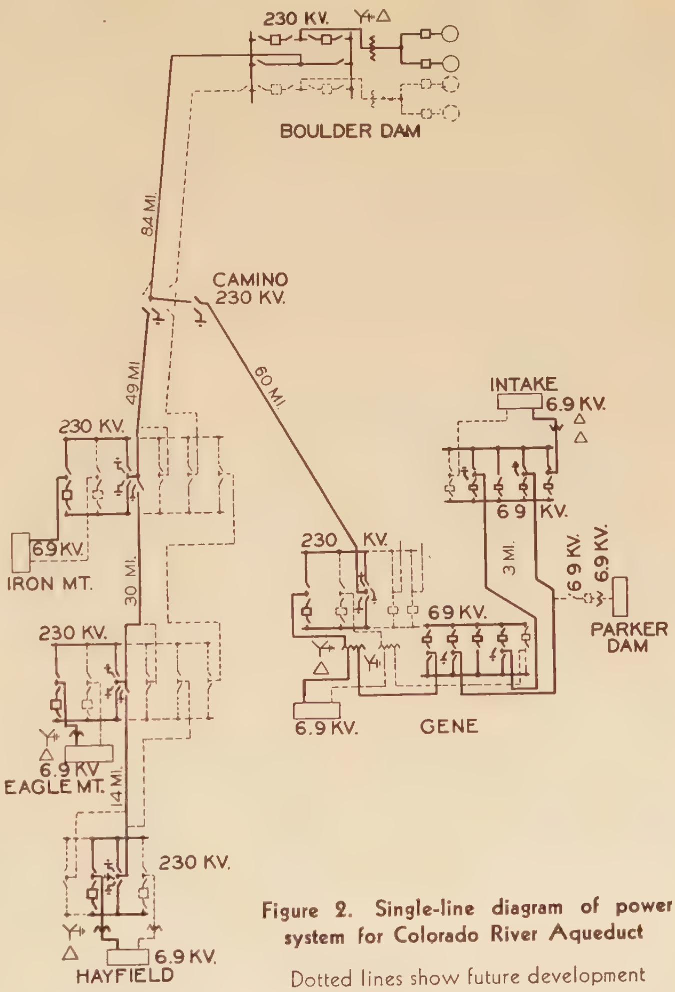


**Figure 2.** Single-line diagram of power system for Colorado River Aqueduct

Dotted lines show future development

constructed. Normally water is pumped direct from the open canal and in case of power failure it overflows into the reservoir. Two of the pumps in the plant have auxiliary inlets from the reservoir permitting water accumulated during a power outage to be pumped out later. The forebay reservoir will hold the full aqueduct flow for 45 minutes and a siphon spillway provides a means of wasting water onto the desert during a prolonged outage. The next pumping plant in the series is Eagle Mountain, figure 13, with a lift of 438 feet, located 40 miles from the top of the Iron Mountain lift. At this plant also, a 100-acre-foot regulating forebay reservoir has been provided. Sixteen miles farther along the aqueduct is located the Hayfield reservoir, capacity 83,000 acre-feet and the Hayfield pump lift of 441 feet, figure 14. At this plant independent intakes are provided from the canal and from the reservoir, so that any pump can draw water from either source.

## Hydraulic Equipment

The pumps are all of the single-stage single-suction vertical-shaft volute type without guide vanes or diffusers. Each pump has a capacity of 200 second-feet. The first installation at each plant consists of three pumps connected to a single discharge pipe. Additional discharge pipes and pumps will be added as required to meet water demands until a total of three discharge lines and nine pumps has been installed in each station.

Few pumps of the capacity and head required for these installations have ever been built, and at the time the work was undertaken considerable difference of opinion existed between various manufacturers as to the best type, speed, number of stages, and depth of setting to insure satisfactory operation. In order to resolve these differences in opinion and to improve pump efficiency the District, with the co-operation of the California Institute of Technology, constructed a pump testing laboratory and carried out a two-year program of model testing prior to the purchase of the equipment. The specifications which resulted from these tests required that each bidder submit for testing in the District's laboratory prior to the award of contract a model of one of the pumps offered. Three contracts were awarded as a result of this competition and each of the contractors was then required to submit for testing a model of each full-size pump to be furnished. Rivalry between competing manufacturers led to keen competition in the course of these tests. Information obtained during tests was used to improve the design and each of the final models showed efficiency between 91.5 and 92.5 per cent. Characteristic curves for one of the Gene models are given in figure 9. The contracts provide for bonuses aggregating $55,000 for each per cent in efficiency in excess of 88 as shown by field tests of the full-sized pumps.

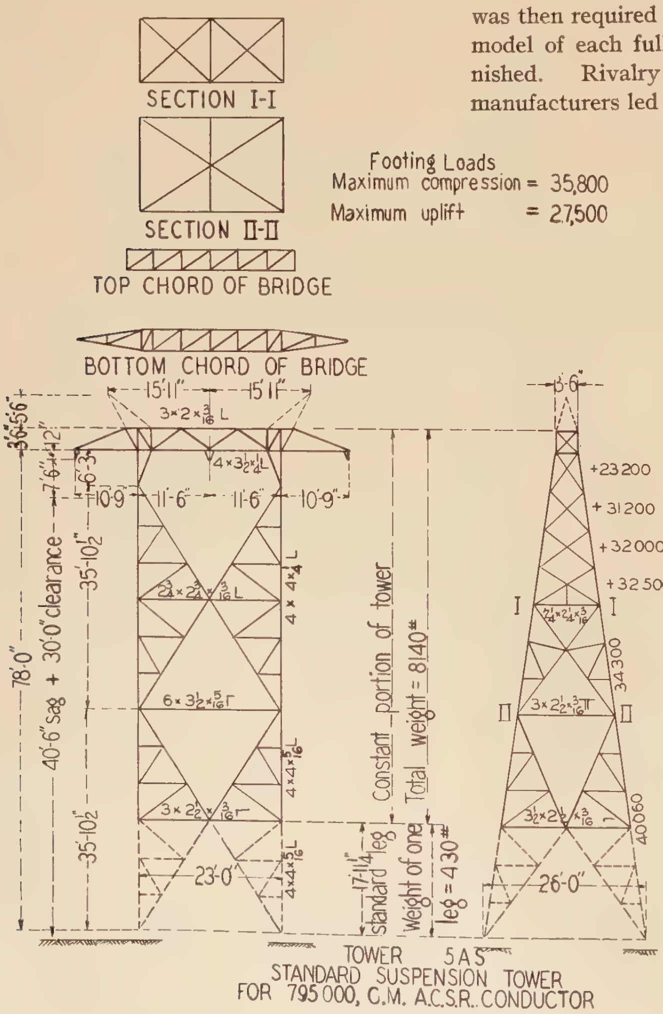


**Figure 3. Standard suspension tower, type 5AS**

For 795,000 circular mils, aluminum steel reinforced conductor

The program of testing also showed certain structural improvements to be desirable in the pump shafts and casings. Under certain conditions, encountered in starting and stopping pumps, the impellers were found to be subject to heavy lateral forces and in order to prevent contact between the rotating and stationary seal rings the shafts were required to be much larger than ordinarily used. Figure 7 is a transverse section indicating structural features of a typical pump. The tests also determined very definitely the depth of the setting below inlet water level necessary to prevent unstable operation and cavitation of impellers. Information of this kind, shown graphically in figure 8, aided materially in the design of the plants.

The casings of all pumps are made of cast steel except at the Iron Mountain plant where high-strength nickel cast iron is used. The casings are heavily ribbed to minimize deflections caused by water hammer and unbalanced side thrusts of the impellers. The pump impellers are all made of high-tensile-strength bronze. Oversize shafts made it possible to reduce radial clearances and increase pump efficiency. Figure 20 is a transverse section through one of the pump houses.

At the Intake plant, each pump takes water from the reservoir through a separate inlet pipe which may be closed independently by plain sliding gates. At the other plants motor-operated butterfly valves are provided in each inlet pipe. Each pump is fitted with a discharge valve and can be unwatered for inspection and maintenance without interfering with the operation of adjacent pumps. Discharge valves are of the rotating-conical-plug type operated by oil cylinders. This valve when fully opened has a circular water passage tapered to correspond to the increasing diameter of the pump-discharge nozzle. In operating the valve in either direction the operating mechanism first raises the plug slightly to unseat it, rotates it to the desired position, then lowers the plug, and reseats it. The oil pressure system is similar to that ordinarily used to operate the Servomotors of hydraulic turbine governors.

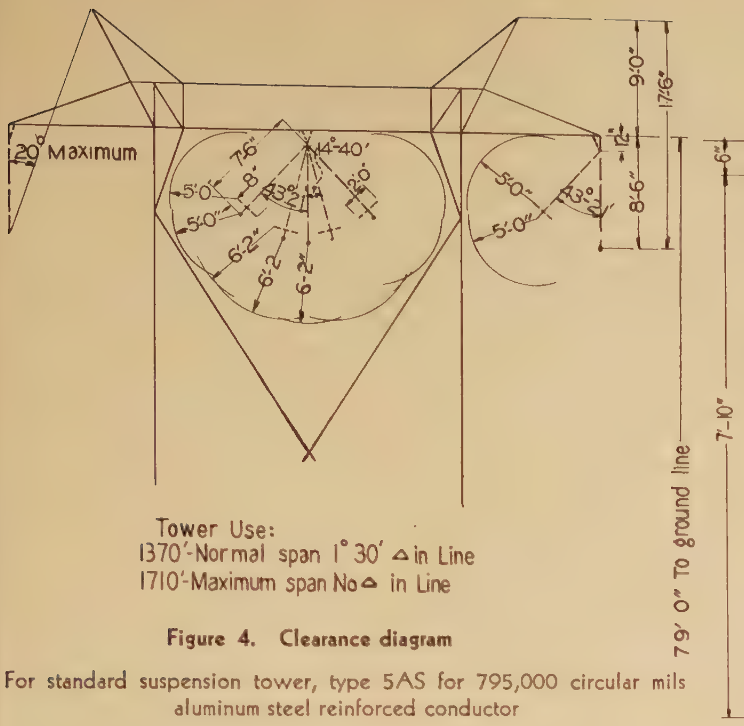


**Figure 4. Clearance diagram**

For standard suspension tower, type 5AS for 795,000 circular mils aluminum steel reinforced conductor

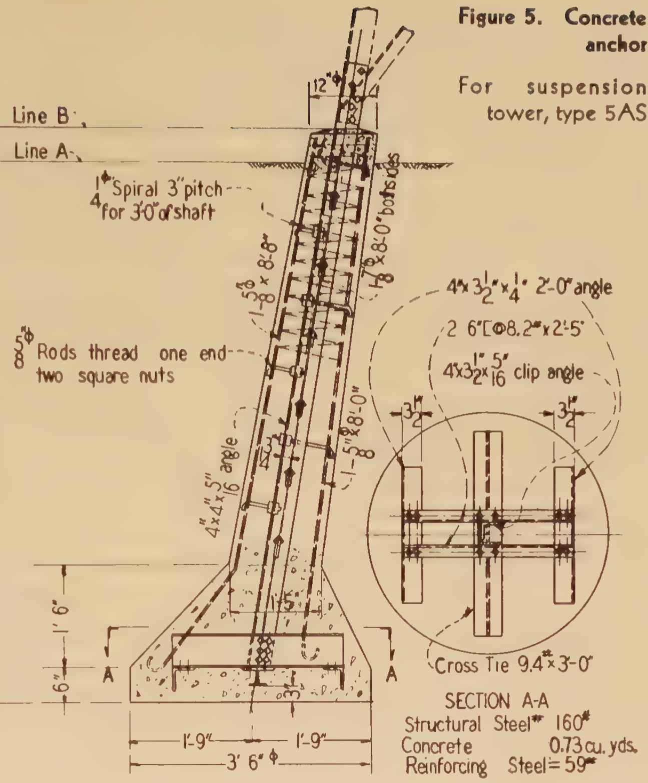


**Figure 5. Concrete anchor**

For suspension tower, type 5AS

Oil for operation is kept under air pressure in accumulator tanks in sufficient quantity for two complete valve operations without recourse to the oil pumps. Pressure surges in the pipe lines, which occur when the pumps are suddenly stopped due to power failure, are held within permissible values by the operation of the discharge valves under the control of a device similar to a hydraulic turbine governor. Upon failure of the power supply the discharge valves close rapidly to the point of definite throttling of the flow. During this interval the moving water column in the discharge pipe comes to rest due to the action of gravity and return flow from the pump is allowed to commence. The latter part of the closing stroke is made very slowly and the reverse flow brought to zero with definite limitation as to increase in pressure. The device is susceptible of adjustment to insure complete closure without excessive pressure rise and before dangerous speed reversal occurs.

## Power Supply

The Metropolitan Water District was one of the three principal underwriters of Boulder Dam. The Boulder Canyon Act authorized the Secretary of the Interior to begin construction of the dam only after he had obtained power contracts guaranteeing the return of the Government's investment within a term of fifty years. Contracts with The Metropolitan Water District, the City of Los Angeles (Bureau of Power and Light), and the Southern California Edison Company, meeting the above requirements were consummated in the spring of 1930. Under its contract the District was allotted and agreed to pay for 1,526,000,000 kilowatt-hours per year (subject to a small annual diminution and the three-year load-building allowance), which is 36 per cent of the firm energy to be developed at the dam. It was also given the first right to use secondary energy which is expected to be available in considerable quantities from time to time. The District also has the right to use the firm energy allotted to the States of Arizona and Nevada, but not used by them. To deliver the full capacity of the aqueduct will require 2,250,000,000 kilowatt-hours annually, or 724,000,000 kilowatt-hours per year in excess of its firm power allotment at Boulder Dam. The aqueduct is designed to provide water for a long period of development of the territory supplied and the growth of the demand will undoubtedly extend over many years. The District's present firm energy supply will undoubtedly be in excess of its requirements for a number of years, but when this firm supply is exceeded the deficiency can be made up by taking over some of the States' firm power, if unused, or by a combination of secondary and standby power to be purchased from other allottees of Boulder Dam power. In addition to these power resources the District owns one-half of a 100,000-kw power site at Parker Dam.

## Transmission Line

The District's power system was designed as an independent unit to efficiently meet the particular requirements of the situation. Sturdy mechanical and electrical construction, high efficiency, and low maintenance were given primary consideration. Of secondary importance were regulation of speed and voltage and the elimination of momentary interruptions. The aqueduct, as a whole, was designed with water storage and carrying capacity sufficient to allow for service outages of seven per cent of the time. This condition practically eliminates any serious objection to momentary interruptions of electrical power service. For this reason no attempt was made to design what could be considered an interruption-proof transmission line. Overhead ground wires and counterpoise were omitted.

The transmission voltage of 230,000 was selected as the result of extensive studies to determine the type and voltage of the system which would give lowest cost during a 50-year period considering maintenance, depreciation, interest, and cost of lost power. A similar study of the transmission problem between Intake, Gene, and Parker power plant resulted in the adoption of 69 kv for this part of the system.

The initial and final development of the system are shown in figure 2. The first installation is a single circuit throughout.

A second circuit from Boulder to Camino will be necessary when the load reaches about two-thirds of its maximum and, unless energy costs are lower than at present, it will be economically advisable to build a second circuit on the west branch of the system when full development is attained.

The lowest elevation of the line is 750 feet above sea level near Gene, and the highest is 3,650 feet between Camino and Boulder. The towers were strengthened for a distance of about ten miles where the elevation is above 3,200 feet. A reduced conductor tension was also used for about five miles in this section. The design for the transmission line towers was selected from a large number of studies, designs, and estimates, including wooden "H" frames, flexible-steel frames with anchor towers at each tenth span, guyed-steel frames, and rigid-steel towers. There was but little difference in the estimated first cost between the various designs. The rigid steel tower was chosen because of its lower cost of maintenance and rugged design. Concrete footings, figure 5, were used throughout the line, except in a few places where towers were set on native rock and excepting the Danby Dry Lake crossing where creosoted pile foundations, figure 6, were found to be necessary to protect the metal and concrete from the corrosive action of the concentrated alkali of the soil. Five different towers are used and the designs provide for legs shorter or longer than standard to meet side-hill conditions. One tower of each type was tested at 50 per cent overload and one standard suspension tower was tested to destruction. In the latter test, failure occurred in the overhanging arm of the bridge at 90 per cent overload.

Two complete lines were located and designed, one for copper and one for steel-reinforced aluminum conductor and alternative bids for all work and materials were taken at the same time. Alternative bids also were permitted on towers to be designed by the bidder to determine the savings, if any, due to the rotated base and waisted designs. The aluminum line proved to be approximately ten per cent cheaper than the copper line and the District design of conventional tower, figure 3, was materially lower in price than any of the others. The line includes 227 miles of steel-reinforced aluminum circuit and ten miles using hollow copper conductor of the twisted I-beam type.

Simple, strong fittings of standard design are used. Suspension clamps were selected after tests at the factory to determine the seat curvature best adapted to minimize vibration stresses. Strain clamps are of the compression type. The aluminum conductor and its steel core are gripped separately, but the clamps for copper compress the entire cable. Vibration dampers of the Stockbridge type are used on both aluminum and copper. Armor rods are also used on the aluminum conductors as an additional safeguard against vibration damage and to protect the conductor against arcs. Arcing horns are not used on insulator assemblies but sufficient clearance has been allowed to permit their installation at a later date if desired. It is a well-established fact that vibration troubles increase with conductor tension and in the interest of long life and low-maintenance cost a conservative value was adopted, namely, a tension of 30 per cent of the ultimate strength at 25 degrees Fahrenheit with a wind load of eight pounds per square foot. The normal level span was fixed at 1,370 feet, or less than the economic span, in the belief that the resulting lower tower height would reduce the lightning hazard.

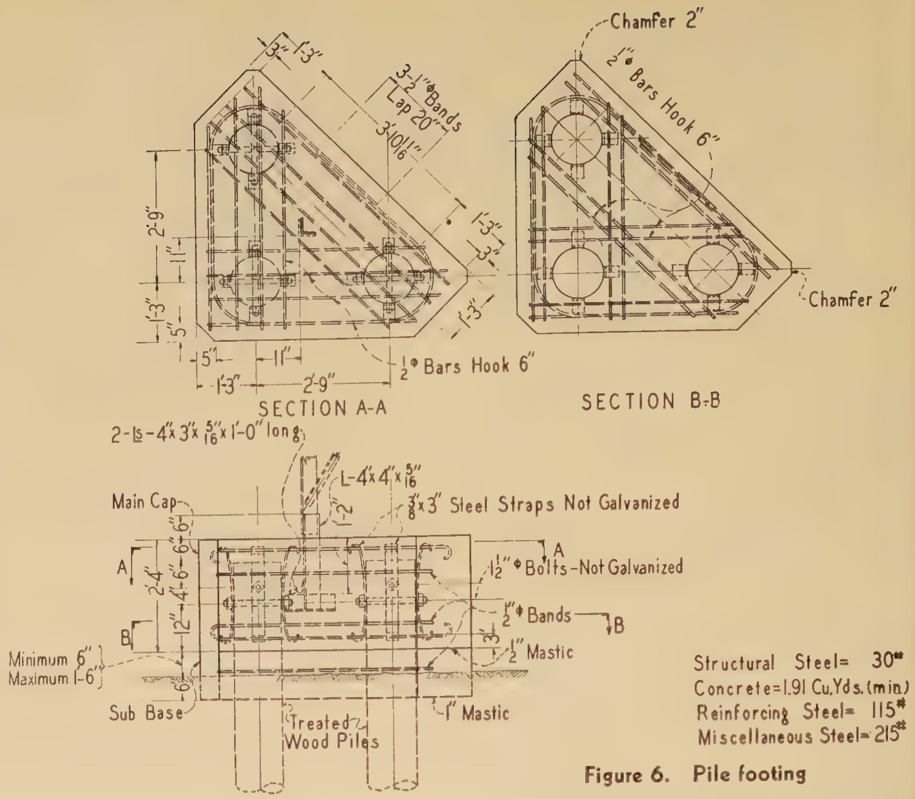


**Figure 6. Pile footing**

For special suspension tower, type 5AH

In establishing clearances between the transmission-line conductors and steel, the dimensions were adjusted to maintain full flashover value of the insulators with the conductor subjected to a wind velocity of about 32 miles per hour. A higher wind velocity will reduce the clearances, but even with an actual wind velocity of 56 miles per hour the clearances will be sufficient to prevent flashovers due to switching surges ordinarily to be expected. The transmission-line profile, of course, is not level and, in order to allow for all possible conditions, clearances were determined for a three-degree angle in the line. The conductor-to-steel clearances are 60 inches with a three-degree angle and a wind pressure of eight pounds per square foot and 74 inches with a 3-degree angle and a wind pressure of $2^1/_2$ pounds per square foot. Figure 4 is the clearance diagram for the standard suspension tower.

The towers carry two ground wires for approximately one mile from each station. Mid-span clearance between conductors and ground wires is 30 feet with aluminum conductors and 20 feet with copper conductors.

## Motors

The completed installation will include 45 6.9-kv synchronous motors ranging in size from 4,300 to 12,500 horsepower. Each motor is equipped with direct-connected main and pilot exciters, and is designed for full-voltage across-the-line starting. All motors are totally enclosed for recirculation of air, are water cooled, and provided with carbon-dioxide fire protection. In the preliminary studies of system design it was apparent that normal characteristics of generators and motors would not give the required stability of operation and a radical reduction in system reactance was necessary. Within practical limits the reactance values of the generators could be reduced at less cost than could the corresponding values of the motors. There was, however, an economic limit to such reduction and, having reached this limit, the improvement of motor characteristics offered the next best possibility. Normal value of synchronous reactance in motors of this size is about 110 per cent, but it was necessary to reduce this value to about 50 per cent to obtain the desired results. In making this determination the problem was set up on an a-c calculating board and solution obtained for the steady-state operating limit. The effect of saturation of the iron in the motors was taken into consideration and their reactance was expressed in terms of equivalent reactance which corresponds to that under actual operating conditions. After the motor characteristics for steady-state operation had been determined, further study was made on a calculating board of the transient conditions occurring when each motor is started. As a result of these studies an equivalent reactance value of 34 per cent at 105 per cent rated output and 95 per cent voltage was specified. Calculations indicated that this figure will give a power margin of about 25 per cent for the present transmission system with four motors operating at each plant.

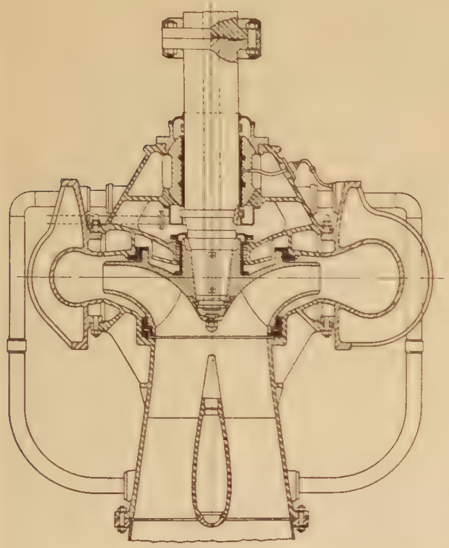


**Figure 7. Transverse section through pump, capacity 200 cubic feet a second against 310-foot head, 400 rpm**

Extra heavy shaft to resist unbalanced radial forces when starting

Main bearing is self-aligning, casing heavily reinforced with cast steel ribs

Across-the-line starting of motors will produce heavy momentary drops in voltage but, since this system supplies no power customers and practically no lighting load, voltage drops are not objectionable. This method of starting greatly simplifies station design. The initial rush of current at starting must be limited to a value that will not allow the terminal voltage to drop below the minimum required for starting the first motor or below the value required for stable operation when more than one motor is in service. It was found that a single amortisseur winding gave a sufficiently low inrush as well as adequate starting torque and this type of winding was adopted because of its substantial construction. The specifications require the motors to produce sufficient "break away" torque to overcome starting friction and the most difficult condition is that which occurs when the initial motor is started in the pumping plant farthest from the generators. As each additional motor is placed in operation, those already in service, with the assistance of their voltage regulators, help to maintain normal voltage giving greatly improved starting conditions. Starting the last motor, however, is the most critical operation as the system is then closer to its power limit. When the 20th motor is started on the single-line system, there will be a margin of stability of about 25 per cent if all regulators are out of service and 35 per cent with the regulators in service. Each motor is required to develop at least 14 per cent of rated torque in starting with normal voltage maintained at Camino. Each motor must bring the pump to synchronous speed with water in the casing, discharge valve closed, and the voltage back of the transient reactance held normal at the generators. At the speed for field application the torque must be sufficient to drive the pump under the above hydraulic conditions with the field short-circuited through a starting resistor or with the field short-circuited upon itself and also with field applied at the most unfavorable angle for synchronizing. These requirements insure that the motors may be easily synchronized regardless of the angle at which the field is applied.

## Receiving Stations

The main transmission line extends to all of the pumping plants except Intake which is supplied with power at 69 kv from Gene. At each plant one bank of transformers has been installed and this constitutes one-half of the ultimate installation. Transformers are wye-connected on the high side with neutrals solidly grounded and delta-connected on the low tension sides. All transformers are water cooled and provided with nitrogen-seal equipment. The 230-kv receiving stations are provided with a main bus and a transfer bus as indicated in figure 15. Because of lack of ground space a high steel structure is used and in the case of the disconnecting switches between the incoming circuits and the oil circuit breaker, the blades of the disconnecting switches are placed in a vertical position. All other high-voltage disconnects are of the horizontal-break type supported on tripods made up of standard high-strength line insulators. The disconnecting switches are motor-operated and controlled from the main bench-

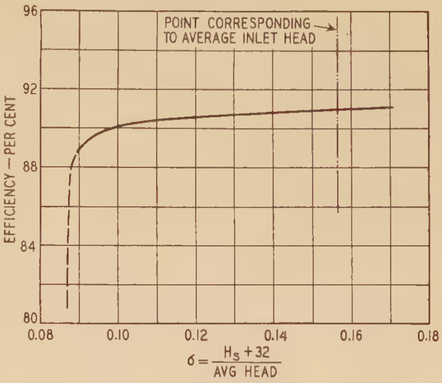


**Figure 8. Typical cavitation characteristic**

$H_s$ = Static inlet head on center line of impeller. Average head = average total pumping head

Note the abrupt drop in efficiency as the inlet head is reduced

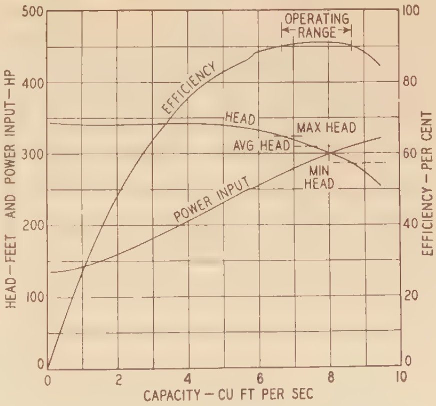


**Figure 9. Complete pump characteristic**

Laboratory test of contractor's model for Gene pumping plant. Model ratio 1 to 5.53, tested at 2,133.5 rpm

Note efficiency of over 90 per cent throughout operating range

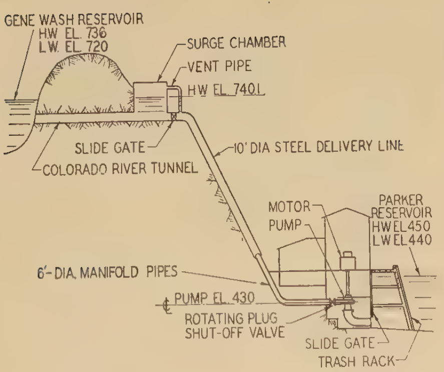


**Figure 10. Intake pumping plant**

Schematic profile

Pump data: Average head 294 feet—capacity 200 cubic feet a second each—speed 400 rpm—motors 9,000 horsepower each

Number of pumps: 3—initial installation
9—ultimate installation

board. The high-voltage oil circuit breakers, having a rupturing capacity of $2^1/_2$ million kva, are of the oil-blast explosion-chamber type and solenoid operated. Figures 16 to 19, inclusive, show the general arrangement of the stations and the design of the switch racks.

The 6,900-volt wiring includes a main and a transfer bus with disconnecting switches and circuit breakers located in a separate building a short distance from the main pump house. When two transformer banks are in service the main 6,900-volt bus will be operated as two sections. Disconnecting switches permit sectionalizing at any one of six places between positions 3 and 7, allowing approximately equal loading of each part of the bus and each bank of transformers. A bus-tie position is provided which by means of disconnecting switches may be connected between either half of the main bus and the transfer bus. Thus the bus-tie oil circuit breaker may be substituted for any motor oil circuit breaker or that for the station light and power position. All disconnecting switches are group-operated and are provided with mechanical interlocking devices and keys to prevent opening or closing of disconnecting switches should the associated breaker be closed, or opening of a circuit breaker cell door unless the circuit breaker disconnecting switches are open, or, connecting more than one circuit to the transfer bus at any one time. The 6,900-volt buses are constructed from one-quarter-inch by four-inch copper bars except at Eagle and Hayfield plants where 5-inch copper channels are used. Special heavy-duty expansion-type bus clamps are provided. All buses are bolted together with $^5/_8$-inch Everdur bolts and all contacts are silver plated. The 6.9-kv oil circuit breakers have an interrupting capacity of 500,000 kva and are rated at 600 and 1,200 amperes. These breakers are of the oil-blast type and are solenoid operated. The oil circuit breaker isolating switches are six-pole, group-operated, and mechanically interlocked with the circuit breakers. All others are three-pole, group-operated switches. All disconnecting switches are enclosed in steel compartments and a set of key interlocks is provided to prevent improper operation.

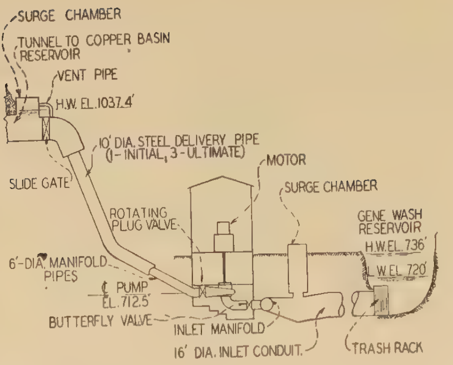


**Figure 11. Gene pumping plant**

Schematic profile

Pump data: Average head 310 feet—capacity 200 cubic feet a second each—speed 400 rpm—motors 9,000 horsepower each

Number of pumps: 3—initial installation
9—ultimate installation

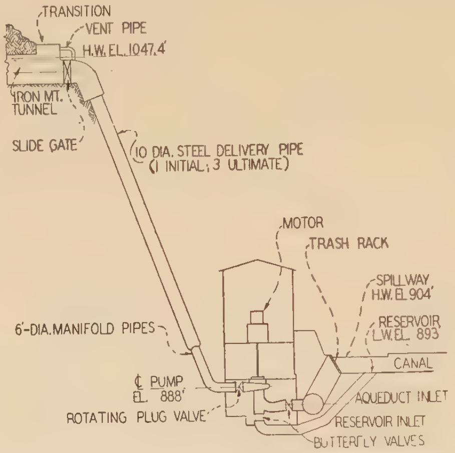


**Figure 12. Iron Mountain pumping plant**

Schematic profile

Pump data: Average head, 146 feet—capacity 200 cubic feet a second. each—speed 300 rpm—motors 4,300 horsepower each

Number of pumps: 3—initial installation
9—ultimate installation

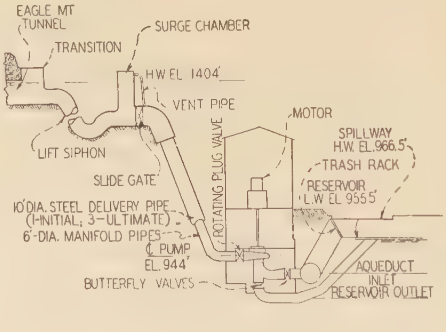


**Figure 13. Eagle Mountain pumping plant**

Schematic profile

Pump data: Average head 440 feet—capacity 200 cubic feet a second each—speed 450 rpm—motors 12,500 horsepower each

Number of pumps: 3—initial installation
9—ultimate installation

## Station Control

The control rooms are so arranged that the operator at the control desk can see all important control panels. The benchboard carries all indicating instruments and the equipment for controlling the motors, 230-kv oil circuit breakers, 230-kv disconnecting switches, and voltage regulators. Station metering equipment and the 230-kv line and transformer relays are mounted on the rear of the benchboard panels. Individual panels or cubicles are provided for each motor. On the front panel of each cubicle are located the annunciator, auxiliary control relays, oil-flow and water-flow pilot lamps, automatic-manual selector switch, pilot exciter rheostat, and control switches for inlet valve, discharge valve, and motor field switch. These controls are in service only when the units are under manual control and are inoperative during automatic operation. The rear panel of

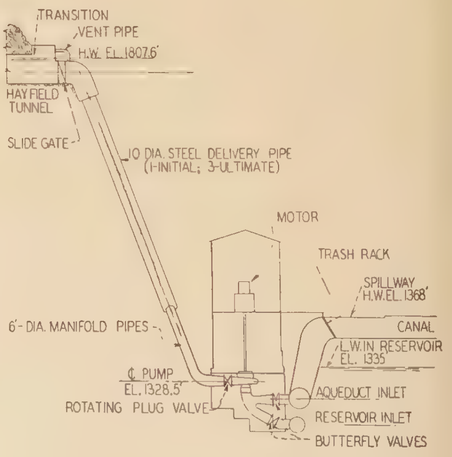


**Figure 14. Hayfield pumping plant**

Schematic profile

Pump data: Average head 444 feet—capacity 200 cubic feet a second each—speed 450 rpm—motors 12,500 horsepower each

Number of pumps: 3—initial installation
9—ultimate installation

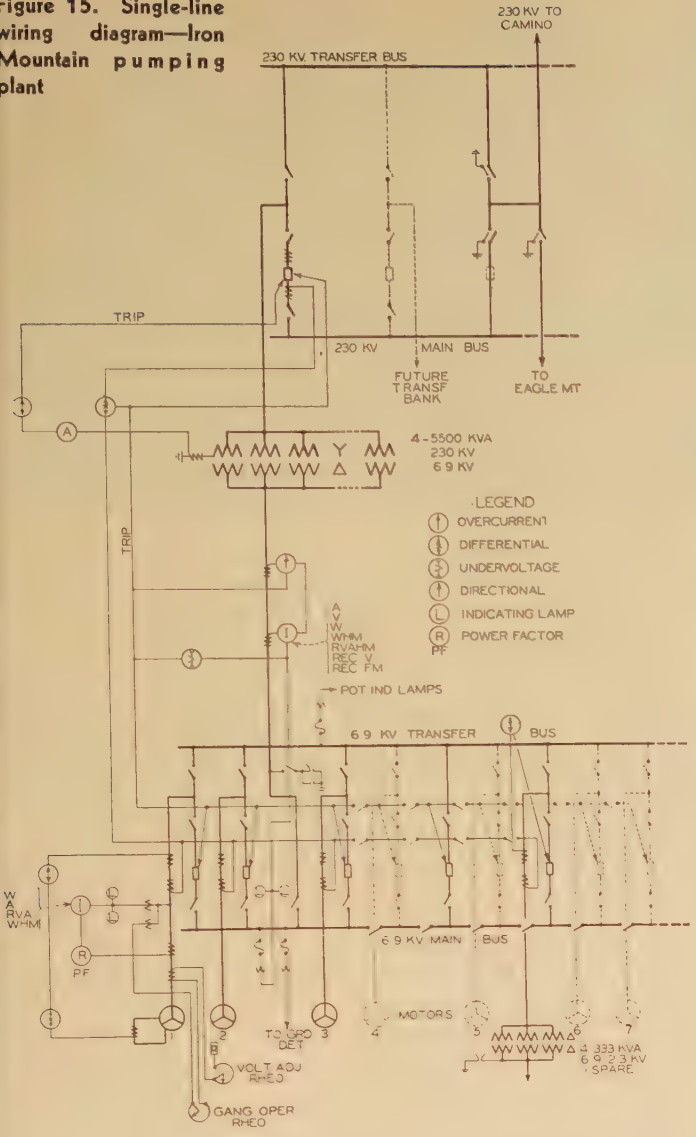


**Figure 15. Single-line wiring diagram—Iron Mountain pumping plant**

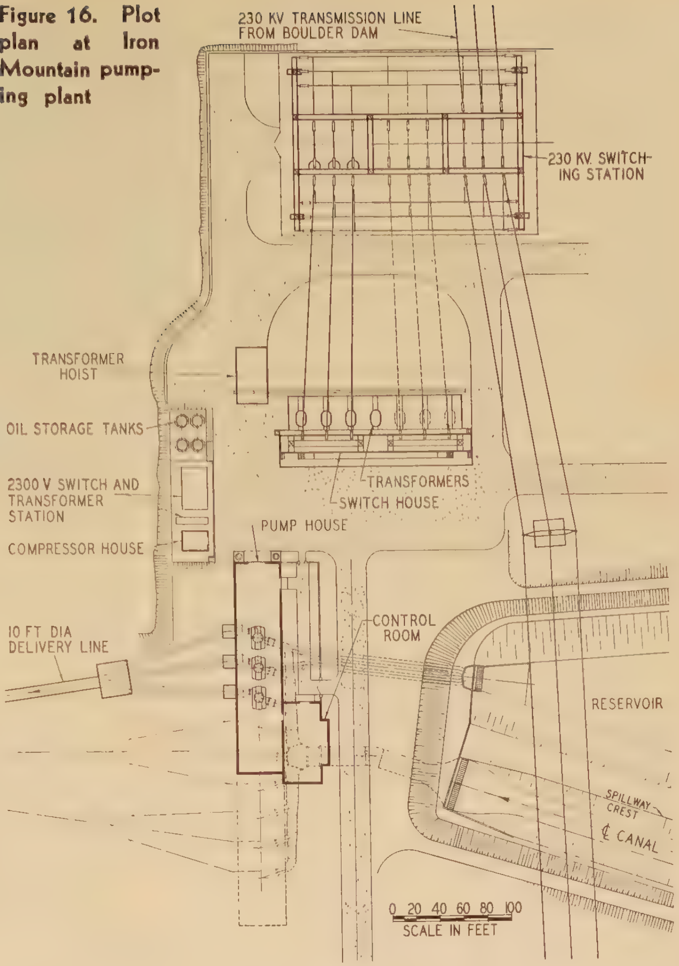


**Figure 16. Plot plan at Iron Mountain pumping plant**

Reservoir receives water from aqueduct in excess of that pumped

Substructure of pump house completed for ultimate of nine pumps

Outdoor hoist for transformer repair

Spare single-phase transformer can be connected in either of two banks without moving

the cubicle carries the overload and differential relays, voltage regulator with its cut-out switch, and the watthour meter. Other panels carrying d-c controls, temperature and water-line indicators, and telephone equipment are located in frames set flush with the walls of the control room. Access to the rear of these panels is obtained from adjacent rooms. Incoming control cables terminate on racks in the control room basement which are provided with terminal blocks for cable conductors and panel wiring.

Under automatic control, before a pumping unit can be started, it is required that the water for cooling and oil for lubrication be functioning properly, that the inlet valve be open, and the discharge valve closed. The pump is then started with the motor field short-circuited through a resistance. As the motor approaches synchronous speed, a synchronizing relay, described later, causes the field switch to close, bringing the motor into synchronism. The voltage regulator is then automatically brought into service and the pump discharge valve opened, establishing flow in the discharge pipe and fully loading the motor. In the normal stopping of a pump the discharge valve is first closed and then the motor oil circuit breaker opened. In case of an emergency shut-down, the motor oil circuit breaker opens immediately and the discharge valve closes under control of the hydraulic surge suppressor previously described.

In the motor-starting scheme, provision is made for automatically applying the motor field when the field flux linkages are a maximum. This occurs twice every slip cycle and the rotor is then in a favorable position for being brought into synchronism. At the instant of maximum field flux linkages the induced field current is zero and the armature current is a minimum. Near synchronous speed the armature current pulsates at a rate proportional to the slip. The field-application relay which is of the wattmeter type closes its contacts at a minimum instantaneous value of the pulsating current. As the pulsations become less frequent, the relay contacts remain closed for a longer period. When the closing period attains a predetermined duration, a series of timing relays operate to close the field breaker at multiples of a half slip cycle later corresponding to a time for maximum field flux linkages. The motor speed at which the field-application relay operates is independent of the voltage. This is accomplished by equipping the synchronous relay with a restraining coil having a torque proportional to the square of the voltage and an operating coil proportional to the motor power input which is proportional to the square of the voltage. After synchronizing the motor the circuit of the potential coil of the wattmeter-type relay is altered so that it becomes a power-factor relay which trips the motor breaker on low power factors resulting from out-of-step conditions.

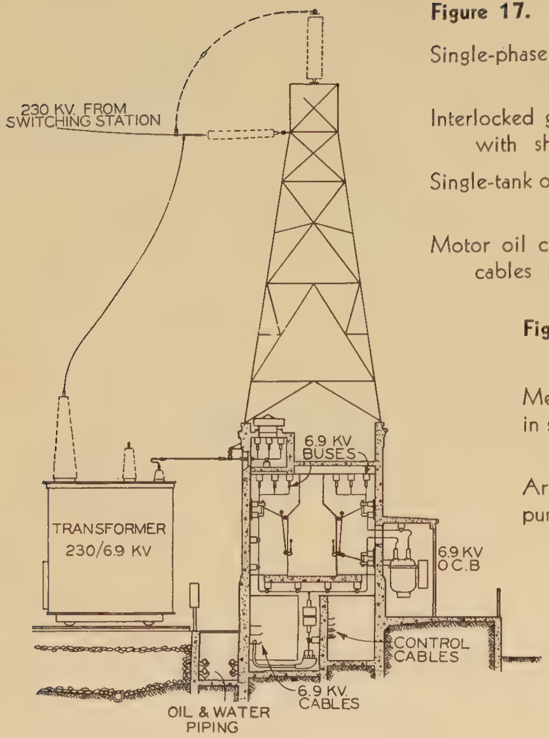


**Figure 17. Section through 6.9-kv switch houses**

Single-phase transformers with short bar connections to buses

Interlocked gang operated disconnecting switches with sheet-metal barriers between circuits

Single-tank oil circuit breakers in cells that open to out-of-doors

Motor oil circuit breakers at switch house with cables in tunnel direct to motor terminals

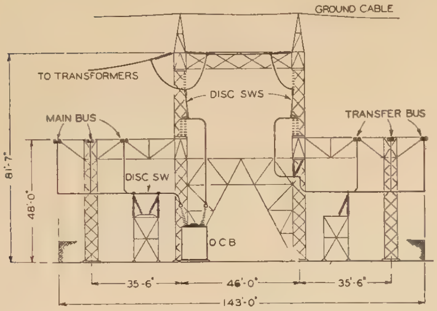


**Figure 18. Transformer section of 230-kv switching station**

Steel structure is latticed column and girder construction

Busses are of copper line conductor supported by strain insulators

Bus taps are copper tubing

Remote controlled motor-operated disconnecting switches are either horizontal or vertical break

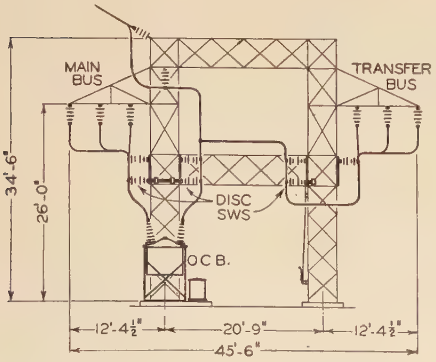


**Figure 19. Section of 69-kv switching station**

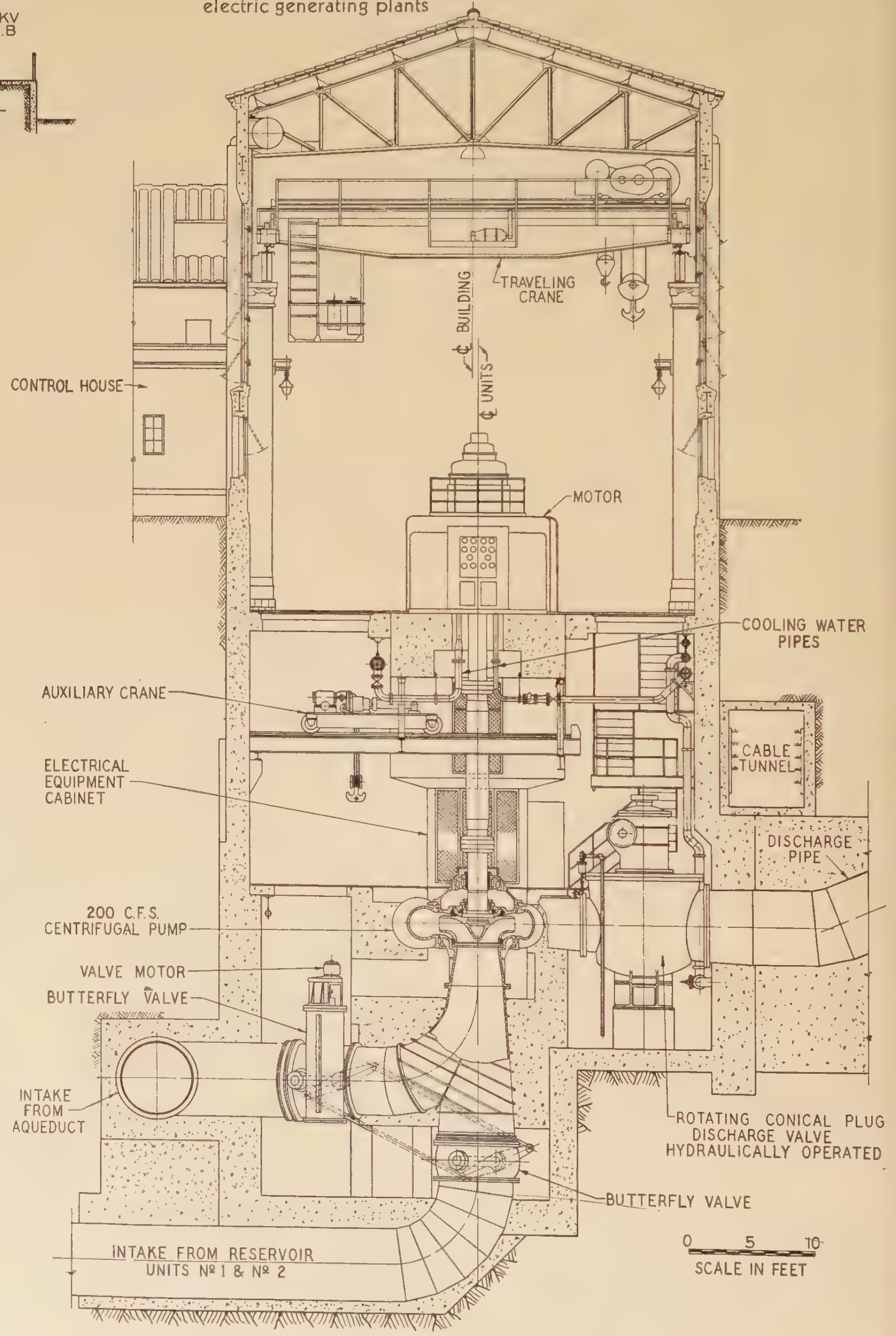
Steel structure is latticed column and girder construction

Disconnecting switches over oil circuit breakers are six-pole, one mechanism per circuit

**Figure 20. Iron Mountain pumping plant—section through pump house**

Mechanically connected butterfly valves in suction permit water to be taken from either the aqueduct or reservoir

Arrangement of pump, motor, cranes, and pump house very similar to that in hydroelectric generating plants



## Protective Relays

Relays for a power system such as this are principally for the protection of lines and apparatus rather than the sectionalizing of the equipment for continuity of service. The simpler types of relays are used and each line and each piece of major apparatus is provided with relays in order to facilitate the location of faults. Phase protection of the 230-kv system is accomplished by directional-type relays at the pumping plants and impedance-type relays at Boulder. The latter are used because of the small difference between currents at Boulder resulting from a short circuit at the extremities of the line and those that flow during the start-

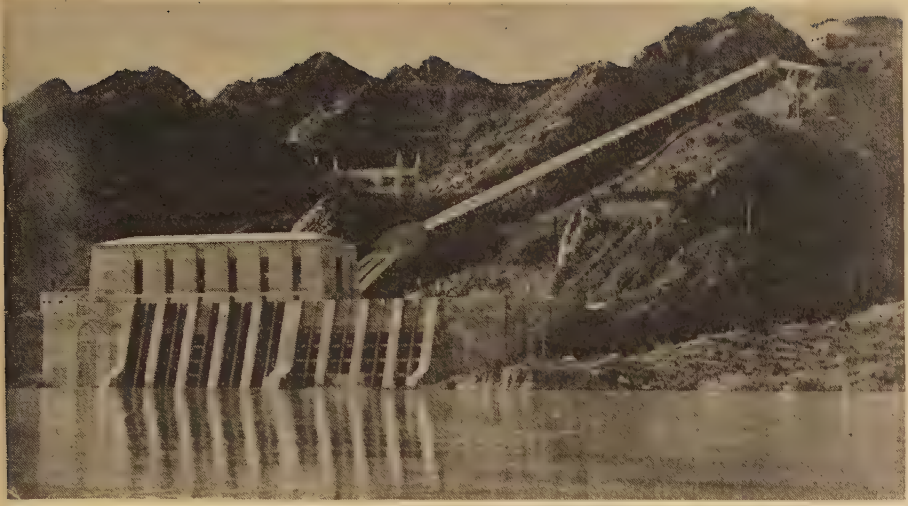


**Figure 21. The Intake pumping plant at the Colorado River**

ing of a motor when the system is near full load.

Relays for line-to-ground faults on the 230-kv line are of the overcurrent induction type and operate from current transformers in the transformer neutrals. At Gene pumping plant, because of the three-winding transformer bank with both 230-kv and 69-kv neutrals grounded, a directional overcurrent relay is used to prevent the 230-kv breaker tripping for a fault in the 69-kv system. The relay has two current elements, one of which measures the sum of the currents in both the 230- and 69-kv neutrals and the other the current in only the 230-kv neutral. When the currents in the two coils are in the same direction, the contacts close. For ground faults on the 230-kv system the only current in the relay is from the 230-kv fault and the relay contacts are set to close under this condition. For faults on the 69-kv system the current in the 69-kv neutral is greater than that in the 230-kv neutral and opposite in direction. Thus the relative direction of current in the coils is reversed and the relay contacts are held open.

For phase protection of the 69-kv lines duo-directional induction-type relays with instantaneous overcurrent relays and cross-connected current transformers are placed at both Gene and Intake pumping plants. For protection of each single 69-kv line and to back up the duo-directional relays, overcurrent induction-type relays are placed at Gene and directional-overcurrent induction-type relays at Intake. The relays at Gene for line-to-ground protection are the overcurrent induction type and at Intake the directional overcurrent type with residual voltage obtained from capacitors on the breakers for the directional element.

Differential protection with induction-type differential relays is used on each motor and each transformer. The motors also have overload relays with a long-time setting to prevent tripping during starting.

## Appendix. Equipment Characteristics

### Boulder Power Plant

#### GENERATORS

| | |
|---|---|
| Number installed initially | 2 |
| Number to be installed ultimately | 4 |
| Kilovolt-amperes each at unity power factor | 82,500 |
| Voltage | 16,500 |
| Number of poles | 40 |
| Speed, revolutions per minute | 180 |
| Short-circuit ratio | 2.74 |
| Direct-axis transient reactance, per cent | 17.5 |
| Moment of inertia ($WR^2$) each—not less than | 105,000,000 |
| Total weight, pounds, approximate | 2,000,000 |
| Outside diameter, feet | 40 |
| Type of insulation | Class *B* |
| Excitation—nominal 250 volts, main and pilot exciter direct connected | |
| Exciter response | 0.50 |

#### POWER TRANSFORMERS

| | |
|---|---|
| Number initially installed | 4 |
| Number to be installed ultimately | 7 |
| Type | Water cooled outdoor |
| Rating of each, kilovolt-amperes, single-phase | 55,000 |
| Voltage | 230,000 Y/16,500 delta |
| Frequency, cycles per second | 60 |
| Impedance, per cent | 10.8 |
| Exciting current at normal voltage, per cent | 2.4 |
| Full-load efficiency, per cent | 99.51 |
| Half-load efficiency, per cent | 99.52 |
| Total weight per unit with oil, pounds | 243,000 |
| Floor space and height, feet | $10^{1}/_{2}$ by $12^{1}/_{2}$ by 30 |
| Quantity of oil per unit, gallons | 9,300 |

#### OIL CIRCUIT BREAKERS—HIGH VOLTAGE

| | |
|---|---|
| Type | Outdoor 3 tank |
| Voltage class, kilovolts | 230 |
| Interrupting capacity, kilovolt-amperes | 2,500,000 |
| Normal current rating, amperes | 1,200 |
| Speed of opening, cycles | Less than 8 |
| Weight with oil, pounds | 204,000 |
| Gallons of oil, per breaker | 15,500 |

### Pumping Plants

#### HIGH-VOLTAGE OIL CIRCUIT BREAKERS

| | Intake and Gene | Gene, Iron Mountain, Eagle, and Hayfield |
|---|---|---|
| Type | Outdoor 3 tank | Outdoor 3 tank |
| Voltage class, kilovolts | 69 | 230 |
| Interrupting capacity, kilovolt-amperes | 500,000 | 2,500,000 |
| Normal current rating, amperes | 600 | 1,200 |
| Speed of opening, cycles | Less than 5 | Less than 5 |
| Weight with oil, pounds | 13,200 | 183,600 |
| Floor space and height, feet | 11 by 6 by 11 | 12 by $45^{1}/_{2}$ by $21^{1}/_{2}$ |
| Gallons of oil | 600 | 13,000 |

#### LOW-VOLTAGE OIL CIRCUIT BREAKERS

| | Intake, Gene, Eagle Mountain, and Hayfield | Iron Mountain Plus Auxiliary Service, All Plants |
|---|---|---|
| Type | Indoor cell | Indoor cell |
| Voltage class | 6,900 | 6,900 |
| Interrupting capacity, kilovolt-amperes | 500,000 | 500,000 |
| Normal current rating, amperes | 1,200 | 600 |
| Speed of opening, cycles | Less than 5 | Less than 5 |
| Weight with oil, pounds | 3,378 | 3,374 |
| Gallons of oil | 82 | 82 |

#### MOTORS

| | |
|---|---|
| Number initially installed | 3 at each plant—total 15 |
| Number to be installed ultimately | 9 at each plant—total 45 |
| Type each | Totally enclosed synchronous |
| Voltage | 6,900 |
| Excitation | 125 volts, main and pilot exciter direct connected |
| Exciter response | 1.0 |

| | Intake and Gene | Iron Mountain | Eagle Mountain and Hayfield |
|---|---|---|---|
| Horsepower rating, each | 9,000 | 4,300 | 12,500 |
| Speed, revolutions per minute | 400 | 300 | 450 |
| Number of poles | 18 | 24 | 16 |
| Short circuit ratio | 2.15 | 2.19 | 2.26 |
| Direct axis transient reactance, per cent | 25.4 | 21.5 | 26 |
| Starting inrush of normal current, per cent | 586 | 646 | 517 |
| Moment of inertia ($WR^2$) each, pound feet$^2$ | 397,600 | 296,000 | 430,000 |
| Type of insulation | Class *B* | Class *B* | Class *B* |
| Total weight, pounds each | 160,000 | 97,500 | 180,000 |

### TRANSFORMERS

| | |
|---|---|
| Type, each single phase | Outdoor, water cooled |
| Frequency, cycles per second | 60 |

| | Intake | Gene | Iron Mountain | Eagle Mountain and Hayfield |
|---|---|---|---|---|
| Number used initially | 12 | 3 | 3 | 3 each |
| Number used ultimately | 24 | 6 | 6 | 6 each |
| Number spare units | .. | 1 | 1 | 1 for both plants |
| Rating kilovolt-amperes each at 230 kv | .. | 22,000 | 5,500 | 15,000 |
| Ditto, each at 69 kv | 2,000 | 11,000 | .. | .. |
| Ditto, each at 6,900 volts | 2,000 | 11,000 | 5,500 | 15,000 |
| High voltage | 69,000 Delta | 230,000Y | 230,000Y | 230,000Y |
| Intermediate voltage | .. | 69,000Y | .. | .. |
| Low voltage | 6,900 Delta | 6,900 Delta | 6,900 Delta | 6,900 Delta |
| Impedance— | | | | |
| 230 to 6.9 kv (per cent) | .. | 9.29 | 9.77 | 10.00 |
| 230 to 69 kv (per cent) | .. | 11.28 | .. | .. |
| 69 to 6.9 kv (per cent) | 9.1 | 20.53 | .. | .. |
| Exciting current at normal voltage, per cent | 1.26 | 2.75 | 3.39 | 3.50 |
| Full-load efficiency, per cent | 99.00 | 99.39 | 99.13 | 99.35 |
| Half-load efficiency, per cent | 99.05 | 99.30 | 99.06 | 99.27 |
| Total weight per unit, pounds | 40,300 | 211,000 | 109,000 | 155,000 |
| Floor space and height, feet | 8 by 8 by 16 | 10 by 17 by 27 | $8^1/_2$ by 12 by $24^1/_4$ | $9^1/_4$ by $15^1/_2$ by 25 |

### PUMPS

#### *Characteristics and Principal Dimensions*

| | In-take | Gene | Iron Moun-tain | Eagle Moun-tain | Hay-field |
|---|---|---|---|---|---|
| 1. Total pumping head including pipe losses in feet—Average | 294 | 310 | 146 | 440 | 444 |
| 2. Ditto—Maximum | 303 | 324 | 156 | 452 | 476 |
| 3. Ditto—Minimum | 272 | 286 | 133 | 427 | 432 |
| 4. Inlet pressure heads in feet when total pumping head is—Average | 14 | 17 | 15 | 20 | 37 |
| 5. Ditto—Maximum | 9 | 5 | 5 | 10 | 5 |
| 6. Ditto—Minimum | 19 | 23 | 16 | 22 | 37 |
| 7. Speed rpm | 400 | 400 | 300 | 450 | 450 |
| 8. Specific speed, gallons-per-minute units | 1,690 | 1,624 | 2,140 | 1,403 | 1,395 |
| Impeller dimensions, inches | | | | | |
| 9. Outside diameter | 76 | 78 | $74^1/_8$ | $81^{15}/_{16}$ | $81^{15}/_{16}$ |
| 10. Inlet diameter | 40 | 40 | $40^7/_8$ | 34 | 34 |
| 11. Width at discharge | 9.703 | 8.833 | $12^5/_{16}$ | 7.0 | 7.0 |
| 12. Inside diameter discharge flange | 42 | 42 | 48 | $40^1/_2$ | $40^1/_2$ |
| 13. Number of vanes | 8 | 8 | 6 | 9 | 9 |
| 14. Shaft diameter, inches | 22 | 22 | 20 | 24 | 24 |

The discharge capacity of each pump at average or rated head is 200 cubic feet per second.

## 230-Kv Transmission Line

### CONDUCTORS

#### *Steel Reinforced Aluminum (ACSR)*

| | |
|---|---|
| Circular mils of aluminum | 795,000 |
| Strands of aluminum | 26 |
| Diameter of aluminum strands, inches | .1749 |
| Strands of steel | 7 |
| Diameter of steel strands, inches | .1360 |
| Diameter of conductor, inches | 1.108 |
| Weight per foot, pounds | 1.093 |
| Ultimate strength, pounds | 31,200 |

#### *Copper*

| | |
|---|---|
| Circular mils total | 510,900 |
| I-beam section core, circular mils | 44,300 |
| Intermediate layer, 22 wires, diameter, inches | .0966 |
| Outer layer, 28 wires, diameter, inches | .0966 |
| Diameter of conductor, inches | 1.004 |
| Weight per foot, pounds | 1.61 |
| Ultimate strength, pounds | 22,500 |

#### *Overhead Ground Wire*

| | |
|---|---|
| Number per tower | 2 |
| Double-galvanized high-strength strand, $^1/_2$ inch with 7 wires | |
| Diameter of each wire, inches | .165 |
| Weight per foot, pounds | .517 |
| Breaking strength, pounds | 21,000 |

#### *Conductor Tensions*

| | Copper | ACSR |
|---|---|---|
| Maximum design tension at elevations over 3,200 feet at 0° F., $^1/_2$ inch of ice and a wind pressure of 6 pounds per square foot, pounds | .. | 14,600 |
| Maximum design tension at elevations under 3,200 feet at 25° F. and a wind pressure of 8 pounds per square foot, pounds | 6,700 | 9,360 |
| Maximum design tension adjacent Gene and Boulder at 25° F. and a wind pressure of 8 pounds per square foot, pounds | .. | 5,600 adjacent to Boulder<br>8,100 adjacent to Gene |

#### *Ground-Wire Tensions*

| | Over Copper | Over ACSR |
|---|---|---|
| Maximum design tension in $^1/_2$ inch steel ground wire | 3,000 | 6,100 |

### TOWERS

#### *Type 5AS, Standard Suspension, Aluminum Conductor*

Designed for light loading (8 pound wind at 25° F.):

1. Normal level span of 1,370 feet, with an angle in the line of 1° 30′.
2. Maximum span of 1,710 feet with no angle.
3. One broken conductor or one broken ground wire.

| | |
|---|---|
| Weight of constant portion of tower, with standard legs, pounds | 10,216 |
| Weight of steel in concrete footings, per tower, pounds | 788 |
| Quantity of concrete in footings, per tower, cubic yards | 2.92 |
| Number of towers | 736 |

#### *Type 5AA, Suspension Tower, Aluminum Conductor*

Designed for light loading (8 pound wind at 25° F.):

1. Normal level span of 1,370 feet, with an angle in the line of 9°.
2. Maximum span of 1,800 feet with an angle in the line of 9°.
3. Maximum span of 2,600 feet with an angle in the line of 5°10′.
4. One broken conductor or one broken ground wire.

| | |
|---|---|
| Weight of constant portion of tower with standard legs, pounds | 11,841 |
| Weight of steel in concrete footings, per tower, pounds | 1,008 |
| Quantity of concrete in footings, per tower, cubic yards | 3.80 |
| Number of towers | 87 |

#### *Type 5AR, Suspension Type for Aluminum Conductors—for use at railroad crossings*

Designed for heavy loading (6 pound wind on wires covered with $^1/_2$ inch of ice):

1. Normal level span of 1,376 feet.
2. Two broken conductors or one broken ground wire.

| | |
|---|---|
| Weight of constant portion of tower with standard legs, pounds | 13,625 |
| Weight of steel in concrete footings, per tower, pounds | 1,528 |
| Quantity of concrete in footings, per tower, cubic yard | 4.92 |
| Number of towers | 12 |

#### *Type 5AD, Anchor Tower*

Designed for light loading (8 pound wind at 25° F.):

1. Span of 1,500 feet, 39° angle in line and no wires broken.
2. Span of 1,700 feet, 39° angle in line, one conductor and one ground wire broken on one side of tower.
3. Span of 1,500 feet for wind and 5,700 feet for vertical loading, 17° angle in line and all wires broken on one side of tower.
4. Span of 1,500 feet for wind and 5,700 feet for vertical loading, 17° angle in line, and on one side of tower all wires broken, on other side of tower one outside conductor and one ground wire broken.

| | |
|---|---|
| Weight of constant portion of tower with standard legs, pounds | 14,836 |
| Weight of steel in concrete footings, per tower, pounds | 2,112 |
| Quantity of concrete in footings, per tower, cubic yards | 8.52 |
| Number of towers | 37 |

#### *Type 5AH, Suspension Tower, Extra Insulation*

Designed for light loading (8 pound wind at 25° F.):

1. Normal level span of 1,370 feet with an angle in the line of 2° 40′.
2. Maximum span of 1,940 feet with no angle in the line.
3. One broken conductor or one broken ground wire.

| | |
|---|---|
| Weight of constant portion of tower with standard legs, pounds | 10,682 |
| Weight of steel in concrete footings, per tower, pounds | 816 |
| Quantity of concrete in footings, per tower, cubic yards | 3.28 |
| Number of towers | 68 |
| Number of towers with pile footings | 24 |

All towers designed to withstand a wind pressure of 13 pounds per square foot on $1^1/_2$ times the projected area of each tower face.

## 69-Kv Transmission Line

### TOWERS

| | Suspen-sion | Dead End |
|---|---|---|
| Weight of constant portion of tower with standard legs, pounds | 11,050 | 16,260 |
| Weight of steel in concrete footings, pounds | 788 | 2,112 |
| Quantity of concrete in footings, cubic yards | 2.92 | 8.52 |
| Number of towers | 7 | 6 |

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## Discussion

**R. W. Sorensen** (California Institute of Technology and Board of Consulting Engineers for The Metropolitan Water District of Southern California): Mr. Gaylord's paper, so ably presented by Mr. Peabody, sums up a most unique and gargantuan project; namely, that of lifting a river of no mean size over 1,600 feet in an upward direction in order that the water of this river might flow steadily from the Colorado River along a 300-mile course to Southern California.

At first glance, one may say why are electrical engineers so much interested in a pumping system? But after all, such a system is made possible only by the availability of a perfectly enormous amount of electric power, over 300,000 kilowatts or one-third the firm power developed at Boulder Dam. Because Mr. Peabody has had a large part in the development of the pumps, and because the unique improvements made therein by research work are so striking and important, he has perhaps left in your minds the idea that the electrical features of this great project may have been somewhat secondary. Such, however, is not the case. Many factors of importance, such as the almost unparalleled management of the general manager and chief engineer, Dr. Frank E. Weymouth, and the work of the many engineers who have carried on the details, as well as the wholly voluntary and extraordinary services of the Board of Directors—have all contributed to an accomplishment, almost complete, of heretofore unprecedented dimensions. For example, this enormous project, costing $220,000,000 is being completed inside the original bond issue. This feature is due to careful analysis of problems of which we may take the transmission line as an example.

A study of the materials used in that line, as given in the paper, shows that high-quality work has been done throughout, but that no overconstruction has been used. For example, the line is built to have a few outages per year; because such outages do no particular harm, they simply result in stopping the flow of water for a short time, which for many years will be immaterial. Thus we find the cost of line necessary to be only about $9,500 a mile, which is indeed a low price for a 230-kv line. Speaking of transmission lines, may I say that in planning these lines some exceedingly interesting problems were encountered.

Before any construction could be started a desert had to be made habitable. In order to do this electric power for construction purposes was provided throughout the length of the aqueduct by running a 69,000-volt line from Colton to the Colorado River, a distance of about 250 miles. Those of you who are interested in transmission lines can readily appreciate the problems pertaining to stability and other features involved in such a line. Like problems are, of course, encountered in the 230-kv line installed permanently for pumping, because it is quite evident that one cannot design a line by simple rule-of-thumb methods and expect that line to perform satisfactorily when the huge motors used are started unless special consideration is given to motors, generators, and line so all factors will work together for such extreme conditions.

I have enjoyed greatly my contact with Mr. Gaylord and the rest of the staff of The Metropolitan Water District of Southern California, because it has been a pleasure to help them analyze with great care each order for machinery, transmission-line conductor, insulators, etc., in a way which would assure for every part of the job the best possible solution at the lowest cost consistent with the kind of construction needed. Nearly all of the equipment described is now installed. In a few months operation will start and, after a reasonable time has elapsed, I expect Mr. Gaylord or some of his staff will be able to present a most interesting paper on the electrical operation of the system.

In the meantime I think the report made in the paper concerning this particular type of application of electric energy is a record worthy of attention as an example of how dependent we are upon electrical power transmission for, without that possibility, the Colorado River Aqueduct of the Metropolitan Water District would have been much more difficult to construct and operate—if not wholly impossible.

# Narrow-Band Transmission System for Animated Line Images

By A. M. SKELLETT
NONMEMBER AIEE

**Synopsis:** A method of transmission and reproduction of line images is described which utilizes a cathode-ray tube for reproduction, the spot of which is made to trace out the line image 20 or more times a second. In an experimental test, a drawing of a woman's head was reproduced with an equivalent total band width of approximately 2,600 cycles. This was made up of two bands, each 1,300 cycles wide for the potentials to the two sets of cathode-ray deflector plates. Analysis of a more complex image, such as that of an animated cartoon shows that such material could be transmitted and reproduced by this method within a total band width of 10,000 cycles.

Means are described for transcribing from drawing or animated cartoon film into recordings (similar to sound recordings) from which the potentials for transmission and subsequent operation of the cathode-ray tube may be obtained.

IT IS inherent in the systems of television on which work is being most actively pursued, that high definition must at all times be realized, no matter how simple the transmitted image may be. Yet many useful images do not contain a great amount of detail and in sending them large blank areas on the available field will be wastefully transmitted. A line drawing or an animated cartoon is an example of such a simple image. If it were possible to transmit the figure and line background, without the blank areas, a great simplification would occur. The system proposed herein was designed to take advantage of this fact.

By the application of proper potentials the bright spot of a cathode-ray tube may be made to traverse any path desired. Furthermore, if the spot is made to follow a certain path, such as that shown in figure 1, over and over, 20 or more times a second, this trace will produce on the end of the tube a stationary image as in figure 2.

Two potentials, each varying with time, are needed properly to actuate the spot. They are applied, the one across the horizontal and the other across the vertical set of plates of the cathode-ray tube. They are directly proportional, respectively, to the $x$ and $y$ co-ordinates of the points of the figure (for example, points 1, 2, 3, etc., of figure 1) taken along the path of the spot in the direction in which it moves. These potentials for the image of figure 1 are shown in graph form in figure 3.

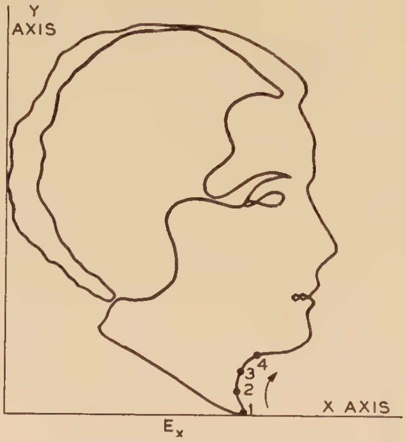

**Figure 1. Resolution of a simple image into a single line. Total band needed for transmission: 2,000 cycles**

## Experimental Apparatus

The reproduction of figure 1 shown in figure 2 was obtained as follows: The $x$ and $y$ co-ordinates were plotted in polar co-ordinate form $[r = (a + x)$ or $(b + y)$, $\theta = t]$ in concentric tracks one inch wide on a cardboard disk 12 inches in diameter. The area under each curve, that is, between the $x$ curve and $r = a$ and between the $y$ curve and $r = b$, was then blackened, and a negative photostat made of it. See figure 4. This disk was mounted on the shaft of a variable-speed motor so that it could be rotated 20 times a second or more and brightly illuminated.

A lens and a radially oriented slit were arranged in such a manner that a portion of the image of the $x$ track fell across the slit. Behind it a photoelectric cell received the illumination passing through the slit. Thus the output of the photocell was directly proportional to the $x$ co-ordinate at each instant of time. A similar setup, mounted alongside, gave potentials proportional to the $y$ co-ordinates.

These two potentials were amplified through separate identical amplifiers and sent over two pairs of wires to the cathode-ray tube.

The method just described of recording the $X$ and $Y$ potential tracks on a disk is suitable for a single drawing but not for animated drawings. For these a record on a long ribbon or film is more practicable.

A device which transcribes from drawings into $X$ and $Y$ potential tracks is called a "transcriber" and the apparatus for obtaining these potentials from the recorded tracks is called the "converter." In figure 5 the complete process from image to image is shown in schematic form, the recordings in this case being on film.

## Band Width

For the simplest type of image in which the drawing may be resolved into a single unbroken line, for example, figure 1, the total frequency spectrum or band width needed will consist of the sum of the band widths needed to transmit accurately the $X$ and $Y$ potentials. These may be assumed to be equal. The band width may then be determined by the analysis of the $X$ (or $Y$) potential variations of a single trace by means of harmonic analysis.

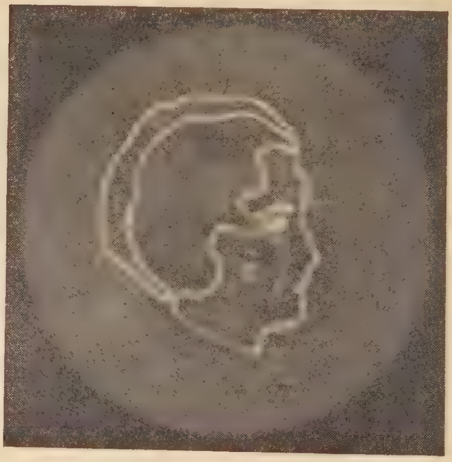

**Figure 2. Photograph of an image reproduced by the first experimental setup. The chief differences between this image and that of figure 1 (from which the recorded tracks were obtained) were traced to errors in the recording**

The magnitude of this potential $E$ may be expressed as a function of time by a

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Fourier equation with a sufficient number of terms.

$$E = f_1 \int_0^{\frac{1}{f_1}} E \, dt + \sum_{n=1}^{\infty} A_n \sin(\theta + \phi_n) \quad (1)$$

Here $f_1$ is the fundamental or trace frequency (about 20 per second) and $A_n$ and $\phi_n$ are the amplitude and phase angle of the $n$th harmonic.

For any drawing the problem becomes that of determining the highest value of $n$ needed for satisfactory reproduction. The band width will be that included between $f_1$ and the frequency of this $n$th component. The band-width will vary with $f_1$ for equal fidelity of reproduction. For instance if $f_1$ is increased to 30, then exactly the same image will be obtained with a band width from 30 to 3,000 cycles as would be realized with one from 20 to 2,000 cycles.

In general the two kinds of detail which will suffer most apparently by the elimination of higher order terms are straight portions and sharp bends. The over-all shape and form of the image and the larger details are dependent on the lower frequencies in the bands. These frequencies are therefore the most important ones. If the bands include enough harmonics to reproduce small details, even in approximate form, the larger details and general form will be reproduced with good fidelity. Thus the band width is largely determined by the fidelity of small detail desired.

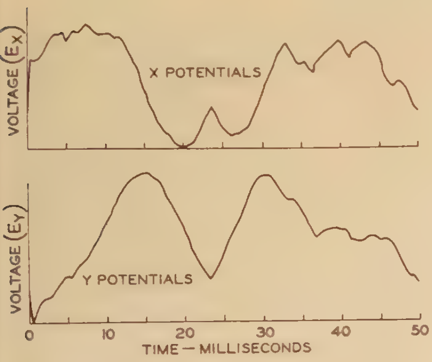


**Figure 3.** Potential variations needed to reproduce figure 1 on cathode-ray tube

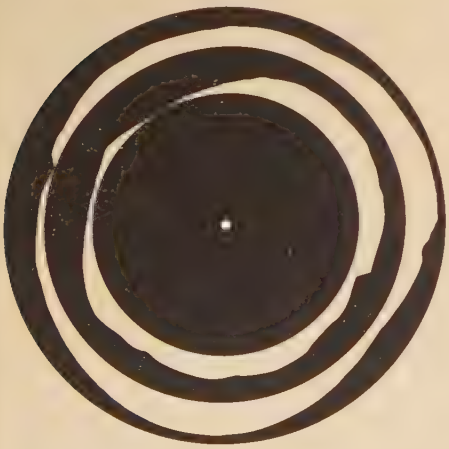


**Figure 4.** X and Y potential tracks used in reproducing figure 3

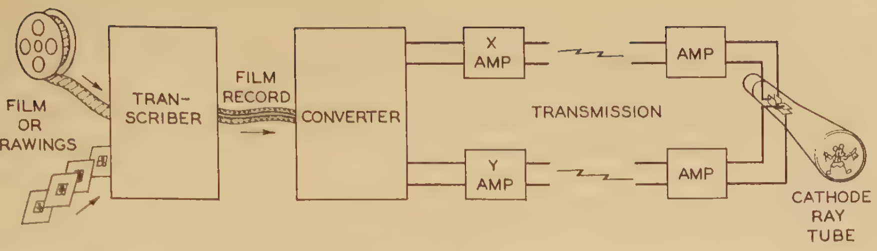


**Figure 5.** Schematic diagram of complete apparatus

Suppose we pick out the smallest detail, in the form of a sharp bend or kink in the curve of a potential function and attempt to determine the minimum frequency needed to reproduce it in approximate form. A little experience in harmonic analysis of typical forms will enable one to determine this frequency by inspection. Generally speaking it will be that frequency the sine wave of which can be made to fit most closely the general shape of the detail. For instance, for a sharp corner, the shape of the wave will determine the curvature that the corner will have when it is reproduced. If the band width extends up to and includes this frequency the detail in the image which gave rise to that in the potential curve will, in general, be reproduced in approximate form. The band width determined in this manner may, therefore, be taken as that necessary for satisfactory reproduction.

A rough check was obtained on the adequacy of this approximate method of analysis by equivalently narrowing the band width of the apparatus used in the reproduction of figure 2. The total band width determined as above for this figure was 2,000 cycles (1,000 cycles for each band). The bands passed by the amplifiers were equivalently reduced to 1,300 cycles each by speeding up the converter and no marked change in the image occurred.

## Dark Paths

For all but the simplest of figures it will be necessary for the spot to traverse paths in the field along which the spot must not be visible. There are two methods of accomplishing this: (1) the beam can simply be cut off by a negative potential applied on the modulating cylinder as the spot passes over such dark paths or (2) it may be made to traverse them so quickly that the visibility of the trace is negligible.

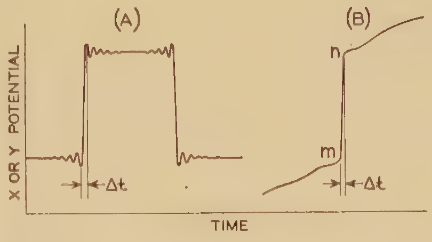


**Figure 6.** Typical wave forms generated in turning the spot on or off

For the first method an additional signal channel is needed and if its band width is made equal to that of the $X$ or $Y$ potential channels, the spot may be turned on or off in an amount of time somewhat less than that required to trace out the finest detail. The wave form would have the general form shown in figure 6$a$ and the highest frequency $f_n$ would be given by

$$f_n = \frac{1}{2\Delta t} \quad (2)$$

For the second method, that is, that of speeding up the spot over dark paths, the wave form required will be in the simplest case similar to that shown between $m$ and $n$ in figure 6$b$. The sharpness of the corners at $m$ and $n$ is determined by the upper frequency limit of the system.

Actually this method requires that either or both the $X$ and $Y$ potentials suddenly change in value so that the spot will abruptly jump across the dark path at such a speed that it is not visible. In figure 2, the velocity of the spot was deliberately increased by a factor of 5 in tracing the line across the neck. A velocity at least twice as great as this is required to make the trace effectively invisible.

Thus it appears that this latter method is to be preferred in general since it requires no increase in band width and no extra channel with its extra facilities.

A cartoon of Walt Disney's popular figure was chosen for determining the frequency band required to reproduce a sketch of considerable complexity. This was resolved into one continuous line such as would be followed by the cathode-ray spot for reproduction. This reproduction would look like figure 7. Parts of the line are over dark paths which are not shown. Assuming that the second method of taking care of these dark paths were used and applying the method of analysis described in the preceding, the total band width necessary for satisfactory reproduction of this image was judged to be 10,000 cycles. This total is made up of 5,000 cycles each for the $X$ and $Y$ potentials.

In the transmission of writing or script, a total band of 10,000 cycles is judged adequate for about seven words of average length. The total band for script is proportional to the total number of letters and spaces or to the number of words of average length.

## The Centering Coefficient

The first term of the series of equation 1 is of importance in centering the image in the field. It is

$$f_1 \int_0^{\frac{1}{f_1}} E\,dt$$

This is simply the total area of the curve over one cycle of period $1/f_1$ divided by the base line $1/f_1$. It thus represents the mean distance of the curve from the zero axis. If eliminated, the shape of the curve and hence also of the image would not be altered, but the centering of the image would vary as the figures moved around in the field. As an example of the effect of this, suppose that the image consisted of a central figure of some complexity and a very simple background. Then if the figure started to walk from the center to the side of the field, the absence of the transmission of this component would hold the figure near the center and the background would slide away in the opposite direction.

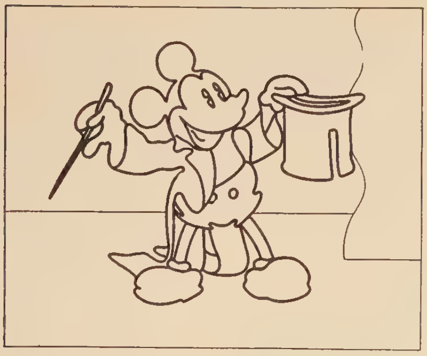
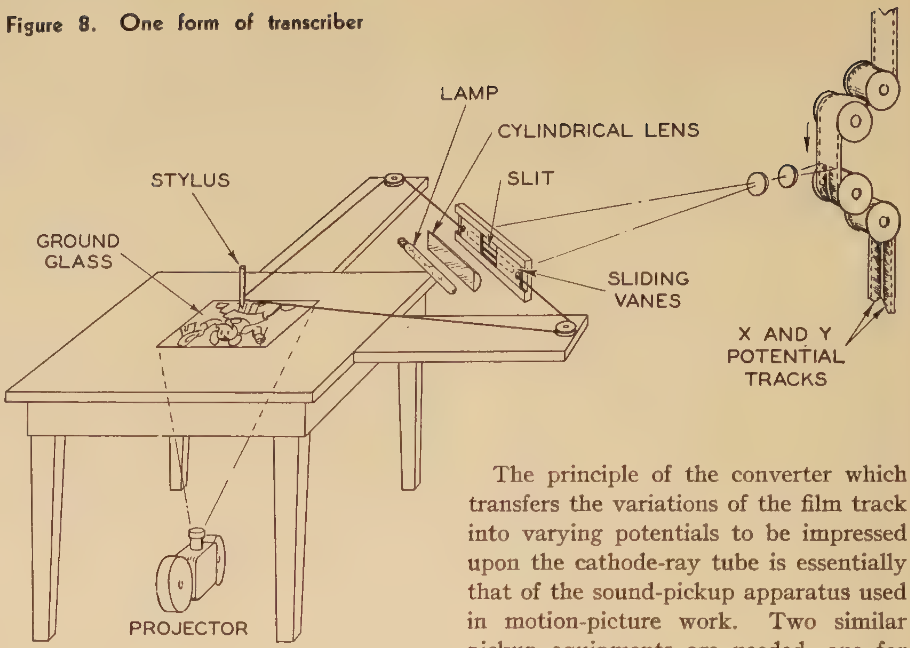


**Figure 7. Total band needed for transmission of this image is 10,000 cycles wide. The spot will move one-half as fast over the figure as it does over the background**

**Figure 8. One form of transcriber**



Ordinarily this component would be eliminated by the apparatus since it gives rise mainly to a direct current. It presents a similar problem in television where it determines the general brightness of the background. Several schemes have been devised to reintroduce or to compensate for it in television and some of these might be used here also. If the image frequencies are used to modulate a carrier, the band may be made to extend to zero on the low-frequency end and this component will then be included in the transmission. The particular method used will depend on the transmission system.

## The Transcription Process

In order to get the $X$ and $Y$ potential recordings, some means of transcribing the original drawings or images into these potential recordings is needed. The simplest method at present seems to be one in which a stylus is manually made to follow the lines of the drawing. This stylus would be coupled up mechanically or electrically with suitable apparatus whose function would be to record simultaneously on film or other media, two tracks, the amplitudes of which would be proportional, respectively, to the $X$ and $Y$ co-ordinates of the various positions of the stylus. Such a machine is shown in simplified form in figure 8. It is arranged to transcribe directly from the film of an animated cartoon. The projector throws onto the ground glass one frame of the film at a time, and the stylus is moved by the operator over the lines of the image.

The principle of the converter which transfers the variations of the film track into varying potentials to be impressed upon the cathode-ray tube is essentially that of the sound-pickup apparatus used in motion-picture work. Two similar pickup equipments are needed, one for the $X$ and one for the $Y$ potential track. If there is a sound track to accompany the cartoon, a third equipment will be needed for it. The standard speed of 90 feet per minute for the film is adequate since with the usual types of pickup this allows a band width of about 6,000 cycles.

## Applications

In urban districts the 10,000 cycles needed to transmit a figure of the complexity of figure 7 could be handled over a single special telephone line. Some equalization would probably be required for the longer circuits which could either be applied to the line facilities or incorporated in the reproducing equipment. For long-distance transmission two circuits of at least program-transmission grade, which are now equalized to 5,000 cycles, would be required, one for the $X$ and one for the $Y$ potentials. Depending upon the degree of definition desired in the reproduced image, circuits of this type might require some supplemental delay equalization.

The following are exemplary of the types of image transmission which are capable of transmission by this method:

1. Drawings, diagrams, and maps either with or without animation, animated cartoons, etc., of purely commercial value. These might include animated drawings depicting the working of new equipment, fashion sketches, etc.

2. Script, including signatures and foreign-language characters, which could not readily be handled by ordinary existing communication facilities.

3. Sketches, primarily of news value. These would include drawings of famous people, places, ceremonies, fashions, and

# Similitude of Critical Conditions in Ferroresonant Circuits

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ASSOCIATE AIEE

RECENTLY a number of articles dealing with the critical conditions in ferroresonant circuits has appeared. However, no simple generalization is possible from these previous methods. The generalization presented in this paper offers certain information pertaining to similitudes of circuits in a surprisingly simple manner. Knowing the critical stable conditions for one reactor, the principle of similitude enables the predetermination of the critical stable conditions for any other reactor using the same grade of iron.

## Equation for Critical Conditions

The circuit referred to in this investigation is one containing a resistance, a condenser, and a saturable-core reactor as shown in figure 1. Assuming that the applied voltage can be resolved into the in-phase and quadrature components, the following vector relation holds:

$$E^2 = E_X{}^2 + E_R{}^2 \tag{1}$$

where

$E$ = applied voltage
$E_X$ = $(E_{LX} - E_C)$ = reactive voltage
$E_R$ = $(E_{LR} + E_{RO})$ = in-phase voltage
$E_{LX}$ = reactive component of the reactor voltage
$E_{LR}$ = in-phase component of the reactor voltage

The critical conditions are defined as points on the volt-ampere curve where $dE/di = 0$. Since $dE/d\left(\frac{ni}{l}\right)$ also equals zero for these points,

$$2E\frac{dE}{d\left(\frac{ni}{l}\right)} = 2E_X\frac{dE_X}{d\left(\frac{ni}{l}\right)} + 2E_R\frac{dE_R}{d\left(\frac{ni}{l}\right)}$$

or

$$E_X\frac{dE_X}{d\left(\frac{ni}{l}\right)} = -E_R\frac{dE_R}{d\left(\frac{ni}{l}\right)} \tag{2}$$

For the unstable condition the above relation is satisfied by two values of current or ampere-turns per inch, while for the critical stable condition the two values of ampere-turns per inch approach a single value.

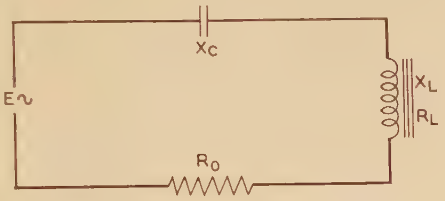

**Figure 1. Ferroresonant series circuit**

## The Generalized Equations

It now becomes necessary to express $E_X$ and $E_R$ in general terms. For simplicity the following assumptions will be made:

$$E_{LR} = \frac{W}{i_1} \tag{3}$$

$$E_{LX} = \sqrt{E_L{}^2 - \left(\frac{W}{i_1}\right)^2} \tag{4}$$

where

$W$ = iron losses of the reactor with sine wave of impressed voltage
$i_1$ = root-mean-square value of the fundamental current.

Since the reactive component of the reactor voltage is proportional to the maximum flux density, which in turn is a function of the ampere-turns per inch,

$$\begin{aligned} E_{LX} &= 4\gamma f n A B_{max} \times 10^{-8} \\ &= nA\beta \end{aligned} \tag{5}$$

where

$\beta$ = $4\gamma f B_{max} \times 10^{-8}$ = a function of $\left(\frac{ni}{l}\right)$
$n$ = number of turns on the reactor
$A$ = cross section area of the core
$\gamma$ = form factor

The in-phase component of the reactor voltage is generalized as follows.

$$\begin{aligned} E_{LR} &= nA\left\{\left(\frac{\#}{Al}\right)\frac{\left(\frac{W}{\#}\right)}{K\left(\frac{ni}{l}\right)}\right\} \\ &= nA\left\{\rho\frac{\left(\frac{W}{\#}\right)}{K\left(\frac{ni}{l}\right)}\right\} \\ &= nA\alpha \end{aligned} \tag{6}$$

where

$\rho$ = density of iron used
$\left(\frac{W}{\#}\right)$ = watts per pound = a function of $B_{max}$ therefore a function of $\left(\frac{ni}{l}\right)$
$K$ = $\frac{i_1}{i}$ = ratio of the fundamental to effective current

Since $\beta$ and $\alpha$ are single curves for any given iron when plotted against the ampere-turns per inch, the two component voltages of the reactor are completely generalized. The values of $\beta$ and $\alpha$ may be obtained experimentally by dividing $E_{LX}$ and $E_{LR}$ as found from (3) and (4) by $nA$ of the reactor; however, these curves are not necessary for the solution of the critical stable condition.

It is now possible to express $E_X$ and $E_R$ as follows:

$$E_X = nA\beta - \left(\frac{ni}{l}\right)\frac{X_C}{\left(\frac{n}{l}\right)} \tag{7}$$

$$E_R = nA\alpha + \left(\frac{ni}{l}\right)\frac{R_O}{\left(\frac{n}{l}\right)} \tag{8}$$

where $R_O$ = series resistance of the cir-

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sketches made by an artist at the location of a news event such as a trial, football game, etc. This last would require a transcriber somewhat different from those described above in that it would have to convert the motion of the artist's stylus immediately into the proper pulsating potentials for sending the image simultaneously with the drawing of it. There are several possible means of doing this.

cuit. Substituting into equation (2)

$$\left\{nA\beta - \left(\frac{ni}{l}\right)\frac{X_C}{\left(\frac{n}{l}\right)}\right\} \times \left\{nA\frac{d\beta}{d\left(\frac{ni}{l}\right)} - \frac{X_C}{\left(\frac{n}{l}\right)}\right\} = -\left\{nA\alpha + \left(\frac{ni}{l}\right)\frac{R_O}{\left(\frac{n}{l}\right)}\right\} \times \left\{An\frac{d\alpha}{d\left(\frac{ni}{l}\right)} + \frac{R_O}{\left(\frac{n}{l}\right)}\right\}$$

Dividing through by $(nA)^2$

$$\left\{\beta - \left(\frac{ni}{l}\right)\left(\frac{X_C}{\frac{n^2A}{l}}\right)\right\} \times \left\{\frac{d\beta}{d\left(\frac{ni}{l}\right)} - \left(\frac{X_C}{\frac{n^2A}{l}}\right)\right\} = -\left\{\alpha + \left(\frac{ni}{l}\right)\left(\frac{R_O}{\frac{n^2A}{l}}\right)\right\} \times \left\{\frac{d\alpha}{d\left(\frac{ni}{l}\right)} + \left(\frac{R_O}{\frac{n^2A}{l}}\right)\right\} \quad (9)$$

Equation (9) is the generalized equation for the critical conditions of the circuit. In this $\beta$, $\alpha$, $d\beta/d\left(\frac{ni}{l}\right)$ and $d\alpha/d\left(\frac{ni}{l}\right)$ have a definite value for any given value of $\left(\frac{ni}{l}\right)$, regardless of the reactor used; therefore the solution of equation (9) will depend only on the values of $X_C\Big/\frac{n^2A}{l}$ and $R_O\Big/\frac{n^2A}{l}$.

By substituting (7) and (8) in equation (1), the generalized expression for the voltage becomes

$$\left(\frac{E}{nA}\right)^2 = \left\{\beta - \left(\frac{ni}{l}\right)\left(\frac{X_C}{\frac{n^2A}{l}}\right)\right\}^2 + \left\{\alpha + \left(\frac{ni}{l}\right)\left(\frac{R_O}{\frac{n^2A}{l}}\right)\right\}^2 \quad (10)$$

## The Principle of Similitude of Circuits

From equations (9) and (10) it is possible to draw certain conclusions. The following apply to the critical stable condition:

1. Two different circuits with equal values of $X_C\Big/\frac{n^2A}{l}$ will have equal values of $R_O\Big/\frac{n^2A}{l}$, and the ampere-turns per inch for the critical stable condition will be equal.

2. For the case above the values of $E/nA$ for the two circuits will be equal.

3. Since the values of $n$, $A$, and $l$ are generally known for any reactor, it is possible to predetermine the critical stable values of $X_C$, $R_O$, $i$, and $E$ for any reactor by a very simple process.

4. The critical values of $R_O\Big/\frac{n^2A}{l}$, $E/nA$, and $\frac{ni}{l}$ when plotted against $X_C\Big/\frac{n^2A}{l}$ are a function only of the type of iron used. (See figure 4.)

5. From the four generalized terms above it is seen that the vector voltage triangles for two similar circuits will be similar; therefore with equal ampere-turns per inch as found under similar conditions the wave shapes of the voltage across the reactors as well as that of the current will be equal. It is then possible to state that under similar conditions in two reactors with the same grade of iron, each unit volume of iron goes through the same cycle wave shape and all.

## Illustrative Example

The following example will illustrate the simplicity of this method:

PROBLEM 1

Reactor 1 has the following dimensions:

$$\begin{aligned} n &= 520 & \frac{n^2A}{l} &= 45{,}700 \\ A &= 2.62 \text{ square inches} & nA &= 1{,}360 \\ l &= 15.5 \text{ inches} & \frac{n}{l} &= 33.5 \end{aligned}$$

When operated in a series circuit with $X_C = 272$ ohms, it gave the following values for the critical stable condition (see figure 2):

$$\begin{aligned} R_O &= 145 \text{ ohms} \\ E &= 224 \\ i &= 0.52 \end{aligned}$$

What will be the corresponding critical stable values for reactor 2 with the following dimensions?

$$\begin{aligned} n &= 352 & \frac{n^2A}{l} &= 17{,}400 \\ A &= 1.72 & nA &= 605 \\ l &= 12.25 & \frac{n}{l} &= 28.7 \end{aligned}$$

SOLUTION

$$\left(\frac{X_C}{\frac{n^2A}{l}}\right)_1 = \left(\frac{X_C}{\frac{n^2A}{l}}\right)_2$$

$$\frac{272}{45{,}700} = \frac{X_{C2}}{17{,}400} \qquad \therefore X_{C2} = 104 \text{ ohms}$$

$$\left(\frac{R_O}{\frac{n_2A}{l}}\right)_1 = \left(\frac{R_O}{\frac{n^2A}{l}}\right)_2$$

$$\frac{145}{45{,}700} = \frac{R_{O2}}{17{,}400} \qquad \therefore R_{O2} = 55.1 \text{ ohms}$$

$$\text{Exp. value} = 53 \text{ ohms}$$

$$\left(\frac{E}{nA}\right)_1 = \left(\frac{E}{nA}\right)_2$$

$$\frac{224}{1{,}360} = \frac{E_2}{605} \qquad \therefore E_2 = 99.5 \text{ volts}$$

$$\text{Exp. value} = 100 \text{ volts}$$

$$\left(\frac{ni}{l}\right)_1 = \left(\frac{ni}{l}\right)_2$$

$$33.5 \times 0.52 = 28.7 \times i_2$$

$$\therefore i_2 = 0.607 \text{ ampere}$$

$$\text{Exp. value} = 0.61 \text{ ampere}$$

This procedure is repeated for other values of $X_c$. The dotted curves of figure 3 shows the critical stable values for reactor 2 predetermined from the experimental values of reactor 1. The discrepancies are due mainly to differences in the flux leakages of the two reactors.

## The Generalized Curves

The critical stable condition for any series circuit can be generalized in terms of $X_C\Big/\frac{n^2A}{l}$, $R_O\Big/\frac{n^2A}{l}$, $E/nA$, and $\frac{ni}{l}$. Figure 4 calculated from four different reactors indicates good agreement with the theory. The tabulated values for the curves are given in table I.

From such a curve it is possible to determine the critical stable values for any reactor almost immediately. To illustrate its use a typical problem will be taken.

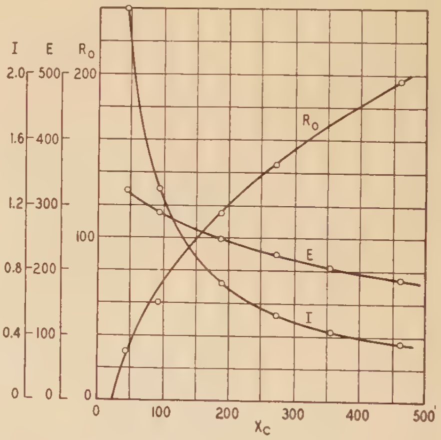

**Figure 2. Critical stable values for reactor 1**

PROBLEM 2

It is desired to design a voltage-sensitive circuit with a critical stable voltage of 200 volts and a critical stable current of 0.6 ampere.

This may be accomplished in a number of different ways. However, from the practical viewpoint the problem is fairly well limited. Starting with a certain value of $X_C\Big/\frac{n^2A}{l}$ the reactor dimensions and the condenser size can be determined. If these values are un-

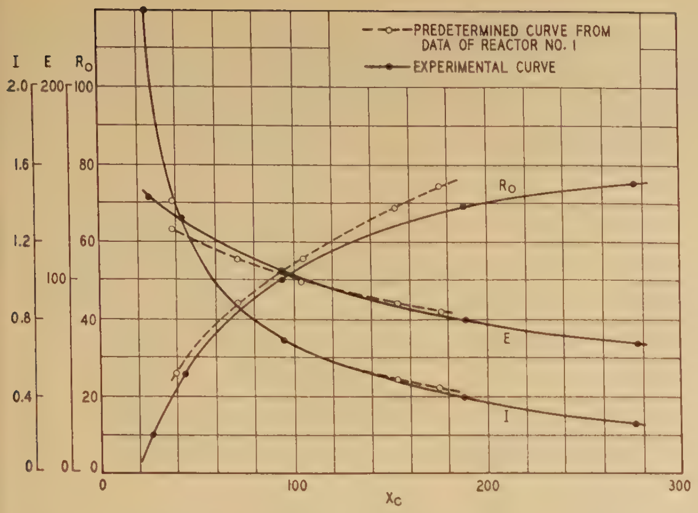

**Figure 3. Critical stable values for reactor 2**

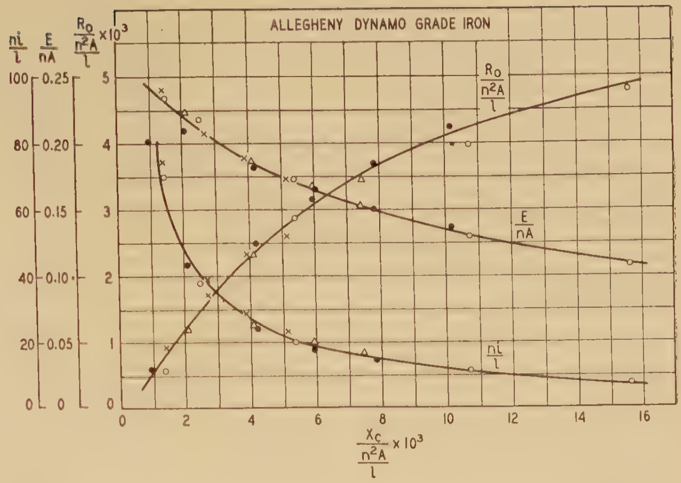

**Figure 4. Generalized curves for the critical stable condition**

practical, another value of $X_C \Big/ \frac{n^2A}{l}$ is chosen and the process repeated.

Starting with $X_C \Big/ \frac{n^2A}{l} = 0.010$

$$\frac{E}{nA} = 0.135 \quad \therefore \; nA = \frac{200}{0.135} = 1{,}470$$

$$\frac{ni}{l} = 12 \qquad \frac{n}{l} = \frac{12}{0.6} = 20$$

$$\text{Volume} = Al = \frac{1{,}470}{20} = 73.5 \text{ cubic inches}$$

This would result in a bulky reactor; therefore, start with a smaller value of $X_c \Big/ \frac{n^2A}{l}$.

For

$$\frac{X_C}{\frac{n^2A}{l}} = 0.004$$

$$\frac{E}{nA} = 0.187 \quad \therefore \; nA = \frac{200}{0.187} = 1{,}070$$

$$\frac{ni}{l} = 26.5 \qquad \frac{n}{l} = \frac{26.5}{0.6} = 44.2$$

$$Al = \frac{1{,}070}{44.2} = 24.2 \text{ cubic inches}$$

$$\frac{n^2A}{l} = 44.2 \times 1{,}070 = 47{,}300$$

$$X_C = 0.004 \times 47{,}300 = 190 \text{ ohms}$$
$$C = 14 \text{ microfarads}$$
$$R_O = 0.0023 \times 47{,}300 = 109 \text{ ohms}$$

If

$l$ = 12 inches
$A$ = 2.02 square inches
$n$ = 530 turns

These values are within the practical range. If a still smaller reactor is desired, a smaller value of $X_C \Big/ \frac{n^2A}{l}$ should be chosen, the size of the core being limited by the space necessary for the coils.

### Table I. Generalization of the Critical Stable Values

| | | Experimental Values $X_C$ | $R_O$ | E | i | $\frac{X_C}{\frac{n^2A}{l}}$ | $\frac{R_O}{\frac{n^2A}{l}}$ | $\frac{E}{nA}$ | $\frac{ni}{l}$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| Reactor 1<br>$n$ = 520<br>$A$ = 2.62<br>$l$ = 15.5 | ● | 43 | 30 | 323 | 2.4 | 0.00094 | 0.000656 | 0.237 | 80.5 | $\frac{n^2A}{l}$ = 45,700<br>$nA$ = 1,360<br>$\frac{n}{l}$ = 33.5 |
| | | 93 | 60 | 284 | 1.3 | 0.00204 | 0.00131 | 0.209 | 43.5 | |
| | | 188 | 114 | 248 | 0.72 | 0.00412 | 0.00250 | 0.182 | 24.1 | |
| | | 272 | 145 | 224 | 0.52 | 0.00595 | 0.00317 | 0.165 | 17.4 | |
| | | 355 | 170 | 205 | 0.43 | 0.00778 | 0.00372 | 0.151 | 14.4 | |
| | | 460 | 195 | 186 | 0.36 | 0 0101 | 0.00426 | 0.137 | 12.1 | |
| Reactor 2<br>$n$ = 352<br>$A$ = 1.72<br>$l$ = 12.25 | ⊙ | 25 | 10 | 142 | 2 4 | 0.00144 | 0.000575 | 0.234 | 69.0 | $\frac{n^2A}{l}$ = 17,400<br>$nA$ = 605<br>$\frac{n}{l}$ = 28.7 |
| | | 43 | 26 | 132 | 1.3 | 0.00247 | 0.00149 | 0.218 | 37.3 | |
| | | 93 | 50 | 104 | 0.68 | 0.00535 | 0.00287 | 0.172 | 19.5 | |
| | | 187 | 68 | 78 | 0.40 | 0.0107 | 0.00390 | 0.129 | 11.5 | |
| | | 272 | 75 | 66 | 0.25 | 0.0156 | 0.00430 | 0.109 | 7.2 | |
| Reactor 3<br>$n$ = 704<br>$A$ = 1.72<br>$l$ = 12.25 | × | 93 | 63 | 290 | 1.3 | 0.00134 | 0.000905 | 0.240 | 74.6 | $\frac{n^2A}{l}$ = 69,700<br>$nA$ = 1,210<br>$\frac{n}{l}$ = 57.4 |
| | | 187 | 120 | 252 | 0.68 | 0.00268 | 0.00173 | 0.208 | 39.0 | |
| | | 272 | 164 | 230 | 0.50 | 0.0039 | 0.00235 | 0.190 | 28.7 | |
| | | 355 | 182 | 209 | 0.40 | 0.0051 | 0.00261 | 0.173 | 23.0 | |
| Reactor 4<br>$n$ = 500<br>$A$ = 2.25<br>$l$ = 12.25 | △ | 93 | 56 | 252 | 1.13 | 0.00202 | 0.00122 | 0.223 | 46.1 | $\frac{n^2A}{l}$ = 46,000<br>$nA$ = 1,125<br>$\frac{n}{l}$ = 40.8 |
| | | 187 | 107 | 212 | 0.62 | 0.00406 | 0.00232 | 0.188 | 25.3 | |
| | | 272 | 139 | 188 | 0.48 | 0.00590 | 0.00302 | 0.167 | 19.6 | |
| | | 339 | 158 | 172 | 0.40 | 0.00738 | 0.00344 | 0.153 | 16.3 | |

## Equivalent Series Circuits

The generalized treatment so far has dealt only with the series circuit. However, the same principle can be used for other circuits by reducing them to the equivalent series circuit.

One practical application of such a scheme is found in the design of the resonant relay circuits. By shunting a high-impedance relay across the condenser of the ferroresonant circuit, relays which normally release at half the closing voltage can be made to open and close at the same voltage when the circuit is tuned for the critical stable condition.

In order to make use of the generalized chart it is now necessary to use the equivalent series reactance and resistance of the circuit. For a relay across the condenser the equivalent series values reduce to a capacity reactance of

$$X_C' = X_C \left\{ \frac{r^2 + X_R(X_R - X_C)}{r^2 + (X_R - X_C)^2} \right\} \tag{11}$$

and a resistance of

$$R' = r \left\{ \frac{X_C^2}{r^2 + (X_R - X_C)^2} \right\} \tag{12}$$

where

$X_C$ = reactance of the condenser used
$r$ = resistance of the relay
$X_R$ = average reactance of the relay

## Conclusion

The principle of similitude offers the simplest and the most practical solution for the critical conditions of the ferroresonant circuit. Some of the advantages over previous methods are:

1. It is not necessary to know the volt-ampere curve of the reactor.

2. The generalized curves giving the complete solution for the critical stable condition are easily determined from any test reactor using the same grade of iron.

3. The principle of similitude presents a clear picture of the effect of varying the circuit parameters.

Although the discussion in this paper dealt mainly with the critical stable condition, equations (9) and (10) also apply to the critical unstable condition. For this latter case there will be two values of $\left(\frac{ni}{l}\right)$, and they will be completely specified by the values of $X_C\sqrt{\frac{n^2A}{l}}$ and $R_O\sqrt{\frac{n^2A}{l}}$.

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## Discussion

**W. B. Coulthard** (Department of Mechanical and Electrical Engineering, The University of British Columbia, Vancouver, Canada): Mr. Thomson makes a further interesting contribution on the ferroresonant circuit in predetermining the limits of stable conditions. However, in applying the principle of similitude to this circuit, care must be exercised.

My criticisms of this method are as follows:

1. The dimensions of the coils and cores must ensure proportionality between the leakage and iron flux.

2. The impedance of the source of supply must be considered. It is well known that different points of instability are obtained when the voltage is varied by controlling the excitation of the alternator and when it is varied by induction regulator control. So to apply the principle of similitude, identical supply circuits must be specified.

3. When reactance preponderates in the supply circuit, due to the phase shift the point of instability does not occur at the peak and dip of the *EI* characteristic but at some points beyond. Instability is now no longer defined by $\frac{dE}{dI} = 0$ but by $\frac{dE}{dI}$ = a negative quantity. Under critical stable conditions it appears that the *EI* characteristic is no longer parallel to the current axis, but there is a slight bend between what are defined as the low- and high-circuit regions. In these circumstances $\frac{dE}{dI} = 0$ does not hold.

**W. T. Thomson:** (1) In order to apply the principle of similitude to any physical problem, it is obvious that the two systems to be compared must be proportional in every way. The accuracy of predetermination will therefore depend on the degree to which this requirement is satisfied.

In ferroresonant circuits it would be impracticable to attempt perfect proportionality in design. However, one should insure similarity within a reasonable degree. For instance, if it is desired to use the *EI* type of core in the reactor, the test reactor from which the data must be taken, should have the same type of core.

The core of the four reactors used to obtain the generalized curves of figure 4 are of the *EI* type, the a-c coils being placed on the outer legs. Figure 4 indicates that the accuracy obtained is sufficient for all practical purposes, and the data should be applicable with reasonable accuracy to other reactors of the *EI* type.

2. The critical points of the circuit vary with different wave forms of the applied voltage to a certain extent, and for accurate predetermination, the impedance of the source should be such that the wave forms are similar. For this investigation a "Variac" was used to insure a minimum of wave distortion.

3. The critical stable condition was defined as the limiting condition of the equation $\frac{dE}{dI} = 0$, and $\frac{dE}{dI}$ equal to a negative quantity does not come under the case of critical stable operation.

For the unstable condition $\frac{dE}{dI} = 0$ will still be points of major interest regardless of whether they represent points of instability or not. With a supply of good regulation $\frac{dE}{dI} = 0$, will represent limiting points of instability.

In general by using reasonable care in insuring proportionality, the accuracy obtained will be sufficient for all practical purposes. It should also be pointed out that up to the present there has been no publication of any other method by which it is possible to predetermine accurately the critical points of ferroresonant circuits in a generalized manner. In articles dealing with ferroresonance, the problem has been turned around backwards, e.g., to calculate the critical points for a given circuit, while the information most desired is of the reverse order; i.e., to be able to start from some specified critical point and design the circuit to give this performance. The information enabling this predetermination must necessarily be of the generalized order such as the one discussed in this article.

Transactions

Papers and Discussions Comprising Pages 131–78 of the 1939 Volume

# Symposium on Operation of the Boulder Dam Transmission Line—General Operation of Transmission Line

By WM. S. PETERSON
MEMBER AIEE

**Synopsis:** The successful operating experience had during the first $1^1/_2$ years with the Boulder Dam-Los Angeles transmission lines of the Department of Water and Power is reviewed in a symposium of five papers. Two unusually severe winter seasons and two lightning seasons, one of which was largely during the construction period, have served to test the line, so that an accurate judgment of its future performance can be made. An historical summary of the use of the line during permanent installation and adjustment of auxiliary equipment and through the period of normal operation to the present time is presented. The manner in which the electrical and mechanical performance has proved the design is developed and the unforeseen problems requiring solution are described. In addition to this general discussion, the excellent performance of the conductor from the standpoint of corona, the outstanding freedom from lightning flashover, are shown in two separate papers. Two additional papers describe the carrier-current supervisory and communication systems and the relay protection system as well as fully discussing the experience had in placing this equipment in adjustment and having successful operation.

THE Boulder Dam transmission line of the Department of Water and Power of the City of Los Angeles, has been in service since October 1936. By virtue of the vagaries of climate, the line has been called upon to withstand lightning, wind, ice, and floods of unusual severity, subjecting the line to many of the extreme conditions for which it was designed, without having to wait the usual long term of years for such conditions to occur.

This circumstance makes it particularly appropriate to review the performance of the line under such operating conditions, for a satisfactory judgment on its long-time performance can thus be made. To present this material together with any special or new problems that have required solution is the purpose of this symposium. It has been found advisable to present this material under several appropriate headings dealing with the mechanical and electrical characteristics of the line, corona, insulation and lightning protection, carrier-current equipment, and relay protection. Where the original description of certain features has not been given heretofore, as for carrier equipment and relays, they are included in these papers.

This line, operating at 287.5 kv, consists of two circuits, each 266.5 miles long, carried on two single-circuit steel-tower lines, except for 40.5 miles carried on double-circuit towers near Los Angeles. It includes such unusual features as 1.4-inch-diameter hollow copper conductor of the segmental type; special suspension clamps; high level of insulation provided by suspension insulator strings consisting of 24 ten-inch-diameter by five-inch-pitch porcelain units; two overhead ground wires, 30 to 40 feet above the conductors; two continuous buried ground wires or counterpoise wires per tower line, with interconnections between tower lines where single-circuit construction is used. Two intermediate sectionalizing switching stations are located at one-third points known as Silver Lake and Victorville stations. Operating as part of the receiving end line sections are two banks of autotransformers reducing the voltage from 275 to 132 kv at Century receiving station (station *B*).

The complete general description of the line and discussion of its various engineering features have been given in a paper entitled "Engineering Features of the Boulder Dam Transmission Line" by E. F. Scattergood,[1] in which paper, as well as in a companion paper,[2] there was indicated the unusual and urgent necessity for this line to be built so as to achieve the utmost reliability. With this object in view, liberal safety factors were employed, in its mechanical and electrical design, and a new step in high voltage was taken, together with the use of the two intermediate sectionalizing stations so that it could carry its normal rated load of 240,000 kw delivered, with unimpaired stability when subjected to two phase to ground faults, removed by dropping a section of circuit. This operating capacity was taken as 80 per cent of the theoretical limit, which was cal-

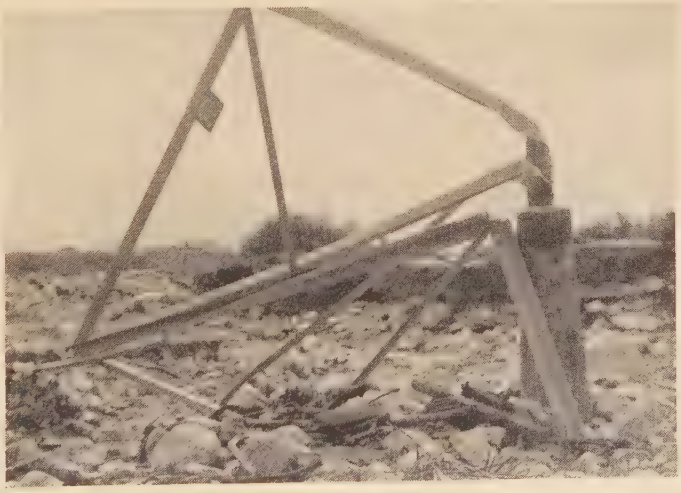

Figure 1. Remains of double-circuit tower after flood

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Paper number **38-109**, recommended by the AIEE committee on power transmission and distribution, and presented at the AIEE Pacific Coast convention, Portland, Ore., August 9–12, 1938. Manuscript submitted May 14, 1938; made available for preprinting July 8, 1938.

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1. For all numbered references, see list at end of paper.

culated without including all of the system of the Department and is therefore also conservative. Factors in obtaining this performance were generators of liberal characteristics, and exceedingly rapid relays and circuit breakers, which would clear faults in approximately 0.1 second or less. The line has an emergency capacity of 300,000 kw delivered, a limit imposed by generator capacity.

The reliability that was built into the system was of outstanding importance when the system went into service. The necessity of making a frequency change cut-over from 50 to 60 cycles at the same time as the line was inaugurated, made the demand for its use so great that essentially the only test the new Boulder system received was the test of service. The very instant that the first Boulder power house generator was available, the transmission system went into service and has continued to give the type of performance anticipated, despite the extreme mechanical loading imposed by a winter remarkable for the worst cold, snow, sleet, and wind recorded during the history of the local weather bureau; followed, a year later, by the thorough test on line location and structural strength, given by a winter having the most severe floods within over 50 years.

## Preliminary Use of Line

The first application of normal voltage to a section of the line occurred on September 20, 1936, when a 90-mile section of one circuit from Los Angeles Century receiving station to Victorville switching station, was excited from the receiving end. This use of the line was made in connection with testing out and developing a neon-tube tower light obtaining its power from capacitive coupling with the line conductors.

The characteristics of the available equipment and transmission lines included in the circuit, and the resultant charging-current effects, made it impossible to build up voltage slowly on the new line, so that on closing the circuit breaker, the voltage immediately came up to normal. The charging kilovolt-amperes was 28,600 as predicted from the calculation of line and transformer constants. No difficulty was experienced with the line or the various circuit breakers and disconnects which were tested at the same time.

## Frequency-Change Considerations

A consideration of consumer's interests had indicated the desirability of changing the frequency on the Bureau of Power and Light system from 50 cycles to the 60-cycle standard used throughout the country. The bringing in of a relatively large new source of power made it desirable and economical to make the change-over when such power was available. Early estimates of generator availability had indicated that the frequency change could start in April 1936, and an organization was built up on that basis. Delays from that date were costly but necessary.

As the first Boulder generator unit did not finally become reliably available until October 22 and the second generator not until November 14, it becomes evident that the transmission system had to go into effective operation immediately as the generators became available.

## Operation for Inauguration

In accordance with anticipated availability of generator units, appropriate ceremonies pertaining to the arrival of Boulder Dam power in Los Angeles were set for October 9, 1936. Broadcasting and other program arrangements required adherence to this date. From the engineering standpoint this inaugural use of the line was important because it was the original tryout. Due to the co-operation of the government and the manufacturer, a generator was made available for that event, although it was not in condition to be released for regular service until nearly two weeks later.

Temporary arrangements of relay equipment and carrier telephone equipment were installed. Both power circuits were available but only one was used in order to avoid self-excitation of the generator.

The program included the use of a large arc to announce the arrival of Boulder power. Line and system arrangements were such that power from Boulder Dam would come over the south circuit, and thence through various system connections and series reactance to a 2,300-volt feeder to a downtown location, where arrangements were provided at the top of 70-foot poles for producing an arc between three-inch-diameter electrodes, arranged vertically, and separated approximately three feet. At the arc the voltage was approximately 1,000 volts, the current was 500 amperes, and the power consumed was 500 kw.

At 2:08$^1/_2$ p.m. October 9, the line was energized to the receiving station at low voltage and reduced frequency. No synchronous condensers were in use. Within three-quarters of an hour, the speed had been brought up to normal and the voltage on the generators was 75 per cent of normal in order to produce normal voltage at the receiving end. The charging kilovolt-amperes was approximately 75,000 which was quite close to the calculated value for lines and transformers.

This was the first full-speed operation of the unit, and a generator bearing began to run hot, so it was necessary to run at reduced speed and voltage from 3 p.m. until required to bring conditions back to normal in advance of striking the large arc at 7:41 p.m.

Other than the difficulty with the generator bearing, no other trouble was experienced in this first test and use of the complete line.

## Further Installation and Test Work

During the following two weeks the relay and carrier telephone installation work was completed and initial adjustments made. Changes in the generator bearing to increase the flow of oil, overspeed tests, and installation and initial adjustments of the generator and transformer differential relay system and other auxiliaries were made. The installation of carrier-current supervisory-control system was under way, but was not completed until a later date.

During the relay installation, the line was charged on several instances for adjustment of potential devices used in connection with the relay system. No difficulties were encountered. It was anticipated that further test and observation and adjustment of the relay system would have to be made during operation. Final adjustments of the telephone system could best be made with the line in operation, so that suitable adjustments of input with respect to the noise level could be made.

## Commercial Operation

Actual use of the line for regular power service began at 7:05 a.m., October 22, 1936, using the south circuit and one generator. Low head in the reservoir limited the generator output to approximately 50,000 kw at full gate. With loads as low as this, it was possible to take the line out of service between midnight and morning whenever desired for adjustment or installation of auxiliary equipment. At the switching stations such work involved permanent installation and adjustment of relay equipment and carrier-current telephone equipment.

Adjustment of pallet switches and other small elements of control were made. The installation work pertained principally to the supervisory control equipment. The line patrolmen took advantage of such opportunities to take out line sections to replace some insulator units slightly damaged by bullets or in course of construction work, and make any other corrections to hardware revealed as necessary by the careful inspection which was being made.

The second generator, unit *N*-4, became available December 28. Both units were put into service immediately at full output with the available head. The bringing in of these units at this time was particularly important in avoiding delay in the program of frequency changing under way. The Boulder Dam system was depended on, and used as a fully dependable system during this exacting time, when keeping adequate reserve for two frequencies was a major problem.

It may be said that these early months of operation constituted the test period for all of this relay, supervisory control, and communication equipment. Observations and tests have been continued to serve as a guide in the proper adjustment of the carrier current equipment and point the way to minor changes of design that may be necessary in any of the elements of the equipment, to meet the requirements, set by the Department, to operate under certain defined unusual circumstances.

By the end of the year 1936 the frequency-change work had been essentially completed, and the system was proceeding on a normal basis. The fourth generator became available March 18, 1937. In general the plant has been loaded up to the limitations imposed by low head until after the runoff of 1937. Since then, the maximum load has been essentially limited by the defined rated operating capacity of the transmission system. Since the Department acquired the system of the Los Angeles Gas and Electric Corporation on February 1, 1937, it became desirable from the standpoint of economy to load the Boulder system as much as possible and use the acquired steam plants for standby. The rapid growth of load on the Boulder system is indicated in table I, showing the kilowatt-hours per month supplied to the low-voltage side of the step-up transformers, the monthly peak output of the main generators in kilowatts, and load factor. In addition the average monthly efficiency of transmission is given. This figure includes losses in the step-up transformers, line, autotransformers, and synchronous condensers. One other transformation from 132 kv to the 33-kv load bus is not included.

During this period of operation, the personnel have had to acquaint themselves; with new types of intricate control equipment, a large and complicated generating plant, a new line arrangement at switching stations, and a line of unusual characteristics and length, and continue operation while extensive installation and test work was going on with such equipment. Under the conditions it is remarkable and the operating group are to be commended on the fact, that a large number of interruptions did not occur from the human element. The operation of the line has been exceedingly reliable and satisfactory. There was a period of ten months operation absolutely free from interruption due to any cause.

Of the five interruptions that have occurred, four have involved the human element as well as the control equipment, so that it cannot be stated beyond all doubt wherein the failure occurred. Such interruptions occurred during operating procedure. The other interruption was caused by a flood undermining a tower and causing relay action which took place correctly. A brief description of each of these cases will be given.

## Interruptions

The first interruption was of very minor importance and occurred at 6:21 a.m., December 15, 1936, during the process of putting the north line back in service after being out on a clearance. The north line was energized for the complete length and had been placed in parallel at Silver Lake and at Boulder. While closing the parallel at Victorville, some faulty action of undetermined origin caused the south line to relay open and interrupt service. The line was carrying 50,000 kw.

The second interruption occurred at 9:11 p.m., January 6, 1937, when the line was delivering 130,000 kw. Sleet had been reported as forming on the conductors at Mountain Pass between Boulder and the Silver Lake switching station. The patrol road was becoming impassable, so it was decided to alternate the load on the north and south line sections between these stations. As will be indicated in the paper on relaying, transients during switching operations had been such as sometimes cause relay action to occur on the incoming line. The north line section had been energized from Boulder and in the process of placing it in parallel with the south line it relayed. Then either the supervisory control indication did not come in correctly, or the Boulder operator did not notice, or else did not wait long enough for the supervisory signal to come in before tripping the south line and interrupting service. Due to the line being charged from the receiving end high voltage existed for one or two seconds until the operator opened the lines so Boulder could get the transmission line ready for resynchronizing.

The third case of interruption did not occur for nearly a year and happened at 10:25 a.m., November 8, 1937, while the relay maintenance crew were making their routine tests on the performance of the relay equipment. In clearing the balanced line, to put them back in serv-

Table I

| Year | Month | Energy to Step-up Transformers (Millions of Kilowatt-Hours) | Generator Peak Kilowatts | Load Factor (Per Cent) | Efficiency of Transmission (Per Cent) |
|---|---|---|---|---|---|
| 1936 | October* | 6.20 | 55,000 | 48.0 | 86.9 |
| | November | 46.70 | 108,000 | 60.1 | 90.4 |
| | December | 67.20 | 162,000 | 55.8 | 91.3 |
| 1937 | January | 80.50 | 156,000 | 69.4 | 93.3 |
| | February | 71.50 | 152,000 | 70.1 | 92.5 |
| | March | 74.20 | 153,000 | 65.3 | 92.0 |
| | April] | 76.40 | 171,000 | 62.1 | 92.3 |
| | May | 76.60 | 167,000 | 61.7 | 94.7 |
| | June | 79.30 | 182,000 | 60.5 | 95.0 |
| | July | 81.60 | 166,000 | 66.1 | 94.9 |
| | August | 85.60 | 216,000 | 53.3 | 94.1 |
| | September | 99.00 | 250,000 | 55.0 | 93.1 |
| | October | 119.10 | 276,000 | 58.0 | 93.6 |
| | November | 117.70 | 277,000 | 59.0 | 93.8 |
| | December | 123.33 | 277,000 | 59.9 | 93.7 |
| 1938 | January | 120.40 | 281,000 | 57.7 | 93.8 |
| | February | 116.60 | 273,000 | 63.5 | 93.8 |
| | March | 111.97 | 267,000 | 56.4 | 93.6 |
| | April | 111.06 | | | 93.8 |

* 235 hours.

ice, some jumpers were inadvertently left so as to involve a complication of several circuits on a relay test panel, in such a way as to have the effect of connecting the secondary of the potential transformer through the residual current coil of the carrier pilot relays. Also due to the short circuit on the potential transformer, voltage on the directional element was such as to cause the relays to indicate a fault on both lines. When the relay test switch was turned to put the relays in operation both lines were tripped.

At the time of this interruption Boulder power plant was carrying 217,000 kw. It is estimated that the maximum receiving-end voltage of the lines was approximately 385 kv at 4.5 seconds after the interruption and that the maximum frequency was 65 cycles per second 5 seconds after the lines opened. Such values are not considered excessive for dropping this much load. These conditions caused no flashovers of line insulation nor difficulty in the autotransformers connected to the lines.

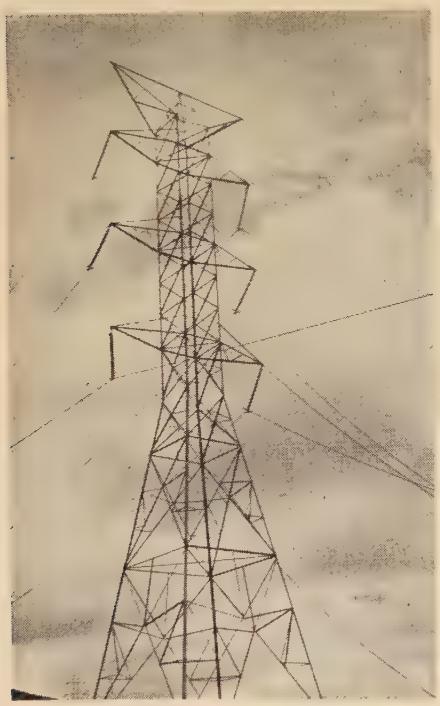

**Figure 2. First tower east of washed-out tower**

The fourth interruption occurred at 6:56 p.m., March 2, 1938, as a result of the undermining of a double-circuit tower by the worst flood of 50 years record in the Los Angeles area. The actual failure began several minutes earlier. At 6:50 p.m., the north circuit relayed out, by balanced line relays, due to a single-phase-to-ground fault on the *A* phase (top conductor). Since the overhead ground wire broke free from the tower on this side, it is believed that this first relay action was caused by the ground wire sagging down on the conductor below. The complete relay and circuit-breaker action required only 3.5 cycles or 0.06 seconds. This is as designed and the circuit-breaker action was without distress. Boulder was carrying 170,000 kw at the time of fault. System voltage drop was scarcely noticeable, and very small power swing took place, the maximum at Boulder being 177,000 kw. Since the operator knew what was taking place, load was then reduced on the Boulder circuit.

Six minutes later the tower completed its process of falling and the bottom conductor of the south line (also *A* phase) contacted ground and was relayed by carrier pilot relays, in $5^1/_2$ cycles at the receiving end and $10^1/_2$ cycles at the Victorville end. The load being carried was 130,000 kw.

This second fault was less severe than the previous one, as very considerable less ground current flowed indicating considerable resistance at the point of fault. The relay time was compatible with the ground currents involved.

The generators speeded up to about 63 cycles 4.6 seconds after the fault. The sending-end voltage did not rise appreciably.

The last interruption occurred at 10:16 a.m., March 29, 1938. It was an illustration of what can happen due to complexity of circuits in a modern power house, where doing some simple but unusual operation brings into action other equipment, possibly out of mind at the time. In this case, while gathering nameplate data for inventory purposes, the circuit breakers for supplying d-c control power over two feeders, were being alternately taken out of service. In this process, the second breaker was opened before the first was closed, removing the control power. Then all normally energized control relays dropped out, establishing a condition which energized the governor shut-down solenoids when the bus was re-energized. This caused all turbine gates to move to the full closed position, where all but one unit latched shut. On this one unit the gates came back to the full open position, but as all of its output was used up in driving the other units and churning water, no power reached Los Angeles, and the Boulder circuits were opened by hand to permit Boulder to clear up its trouble and get the line ready for synchronizing. The load on the machines at Boulder at the time was 230,000 kw.

The Boulder speed dropped to 45 cycles about 30 seconds after separation. The regulators were set to maintain 17,000 volts at the generator. The units were then put on hand control, and gates opened to bring the speed up. Due to no load, they came up more rapidly in speed than the regulator could adjust voltage, considering the heavy field current and the effects of line-charging current with increasing speeds. The leading current also acted on the cross compensation of the voltage regulators, causing them to regulate seven per cent higher than their setting. The maximum voltage at Boulder was approximately 385 kv. The receiving-end voltage was not appreciably different because of the very large lagging exciting current taken by the autotransformers at the receiving end, with high voltage.

## Electrical Loading and Performance

Due to the continuous use that has been made of this line there has never been opportunity to conduct any program of accurate testing to determine the line characteristics. However, with open-circuit conditions and normal voltage at the receiving end, switchboard readings were taken of current and voltage on the high-voltage side at Boulder. A comparison of these results with values determined by transmission system constants calculated with slide rule, for the same complete circuit, revealed that the calculated sending-end voltage was 238,000 while the test average was 239,000 and the calculated current was 200 amperes while the test average was 194. Such constants were determined on the simple isolated circuit basis, without refinements including ground wire effects, or height above the ground, etc. This is sufficient check to give assurance that the circuit is operating about as anticipated. The general performance under load is also as expected from calculation of performance.

In the design work, the assumption was made that the generator terminal voltage would in general be held constant at the normal value, with a fixed setting of the voltage regulator. In actual operation a slightly different policy has been followed to date. The regulator setting is changed with the load, ranging from 90 per cent voltage at very light loads up to 105 per cent at the higher loads. This gives operation in accordance with the criterion for minimum line loss, and also permits the synchronous condensers to operate at lower outputs.

The high efficiency of the line is indicated in table I.

Operation of the line has as yet developed no conditions which provide a full check on the stability limit. However, some verification of design can be obtained from the clearing of the first circuit. During the trouble of March 2, 1938, when a tower was taken out by flood at a time when the load was 170,000 kw, the relay and circuit-breaker action was so prompt that only a single-phase-to-ground fault resulted. However had slower circuit breakers been used the fault would presumably have had time to develop into a two-phase-to-ground or three-phase fault. This proved to be the case when a very similar tower failure took place on the Department's 110-kv double-circuit line, where an $A$-phase-to-ground fault developed into a two-phase-to-ground fault within 3 cycles and in 13 additional cycles became a three-phase fault. For a three-phase fault at this load the more permissible duration of fault to avoid instability is of the order of one-third second. If the customary speeds of fault removal, such as 20 to 30 cycles had been used, this fault would probably have produced instability. As it happened, there was hardly an observable flicker of voltage and hardly any power swinging. Operation was perfect until six minutes later when the tower had fallen so as to involve the second circuit.

## Mechanical Characteristics and Loading

### Conductor

All of the line carried on single-circuit towers is designed to carry one-half inch of radial ice loading with a wind loading of eight pounds per square foot of projected area, with a safety factor of $2^1/_2$ on the ultimate strength. The nearest approach the line will probably have to these loadings occurred during the winter of 1936–37.

The first evidence of sleet formation on the line occurred during December 1936 when a few spans at the top of Cajon Pass were observed to have one-half to three-fourths inch of ice measured radially in the vertical plane, but having very little thickness on the sides. At this time the wind had a velocity of approximately 30 miles per hour. Similar conditions existed at another mountain pass between Boulder and Silver Lake stations. The conductor completely recovered to its original normal sag after the loading was removed.

The sleet formation in Cajon Pass was watched with considerable interest as an effort was made in locating the line to choose proper elevations, and the appropriate slope of the mountains, so that sleet difficulties would be minimized. The experience of some other lines in this area had been that sleet and snow has formed up to diameters in excess of eight or ten inches and broken down conductors and structures. In the storm under discussion some lines had such difficulties. It is now believed that the route selected is probably a good choice.

During the period of construction and operation, several periods of relatively high wind velocity, probably up to approximately 50 miles per hour, have been experienced without giving any trouble. This is considerably below velocities that would give mechanical trouble. The design of clearances is based on a wind velocity of 70 miles per hour without ice so there was no real danger of flashover at lower velocities.

During the year beginning September 1935, while construction work was in progress a survey of line vibration was carried on, in which 71 locations likely to be favorable to producing conductor vibration were investigated, by using a recorder employing an inertia arm. If any appreciable vibration was indicated by this instrument, a smoked-chart recorder was put in place to measure amplitude. Such were installed in 44 of the above locations.

Approximately 18 miles in scattered locations or seven per cent of the total line, gave evidence of vibration in excess of one-half inch double amplitude at a point six feet out from the clamp, and in excess of one per cent of the time during which wind was favorable for vibration. In only one case was this amplitude maintained for as long as five per cent of the time that the wind was favorable for vibration. At this same location the amplitude reached the maximum of any place on the line, which was only $1^1/_8$ inches, double amplitude. This highest amplitude only prevailed for 0.01 per cent of the time that wind was favorable for vibration.

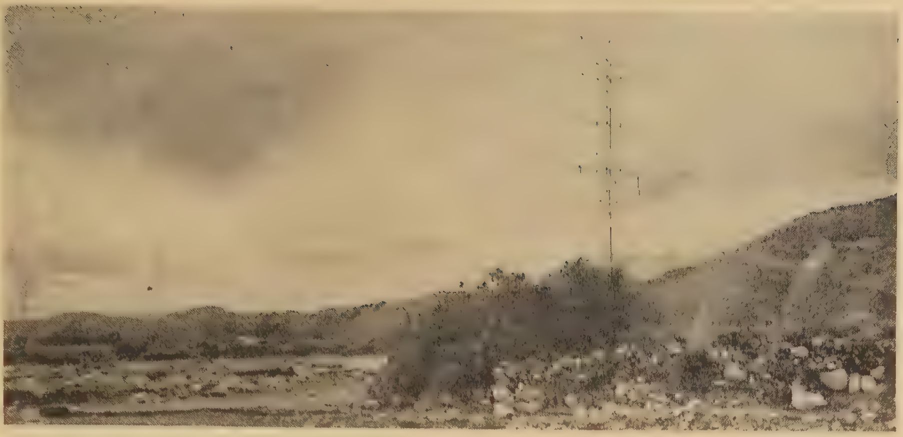

**Figure 3. Towers west of washed-out tower**

Based on the recorded data, none of the locations had vibration of sufficient extent to lead to fatigue failure within a 50-year period. This knowledge is based on fatigue studies on the conductor used. However, in order to be conservative and make allowances for differences that might exist due to the relatively short time of survey at each location, it was decided to equip the 18 miles mentioned above with dampers.

The studies by the Department have served to indicate that the conductor being used has a high degree of self-damping, and is entirely satisfactory in its performance in resisting fatigue failure.

### Hardware

The free-center-type of suspension clamp used on this line has operated very successfully. Although the cable lies in pivoted saddles without clamping, there has been no creep. The knife-edge pivots used have shown no wear where examined, and no wear was indicated for a clamp carrying normal load in a vibration fatigue test on the cable. During the recent tower failure due to the flood, the center wedge grip engaged the body of the clamp and held dead end strains on the cable as anticipated.

The wedge-grip strain clamps and conductor connectors have proved entirely satisfactory. One refinement however was necessary and became evident at the start of the stringing operations. Conductor stringing was started with one crew in the Kingston Valley section of the line on March 15, 1935, and this was followed by a crew in the Silver Lake section on March 21, 1935. The first span of cable erected at Silver Lake pulled out of the dead-end fittings during the erection process, and this was followed by a similar occurrence at Kingston a few days later. We had previously broken, in laboratory tension tests, several hundred pieces of this cable when dead-ended in these same fittings and in every case the dead-end fittings functioned perfectly. However, the cause of the trouble was found to be in the design of the inner wedge or chuck of the dead-end fittings. The chuck was not flexible enough to accommodate certain combinations of manufacturing dimensional tolerances of cable and dead-end fittings. All chucks were additionally slotted to make them more flexible and no additional trouble was experienced.

In connection with the discussion of hardware it is of interest to call attention to a special unforeseen condition that exists along about seven miles of line. At this point the line is proceeding in a westerly direction after going through Cajon Pass. Here the line is running in the foothills parallel to the axis of the mountains, but there are frequent small canyons at right angles to the direction of the line. The prevailing winds, which are frequent and of moderately high velocity, are from the north and flow down these little canyons with varying velocity in adjacent canyons. The result is that adjacent spans of the line have unequal and continually shifting wind loading, which produces considerable longitudinal motion as well as the normally anticipated transverse swing of the insulator strings.

Due to this action, the commonly used bent-rod type of hanger bracket, which has a hooked end carried by holes in clip angles attached to the cross arms, is causing some wear at the points of support. An improved type of hanger, devised so as to give rolling action rather than sliding action, is being designed for use at this location. For the remainder of the line this hanger has given no such difficulty.

It was also observed with this type of hanger, that in comparison with structural-steel or plate type of hangers, that there was more tendency for the clevis pins to move endways and eventually bring the cotter key against the clevis where it could wear. The exact cause of the action is not known, but may be due to the large eye and the curved surface on which the pin rests, coupled with the larger motion with the wind that comes with the use of the hollow conductor of light weight. To eliminate any worry of failure due to this cause the pins were replaced with bolts and slotted nuts with cotter key to lock the nut.

The seven-mile section here referred to had the same type of longitudinal motion take place on the overhead ground wire, causing the clamp to swing 45 degrees. The result was excess wear on the trunnion pivots of the suspension clamps at such locations. At the present time, designs are being made for special clamps, to withstand this kind of action. This type of wear is not found elsewhere on the line.

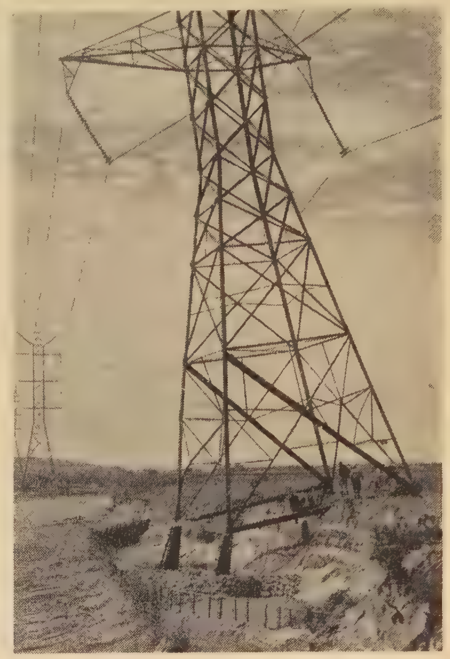

**Figure 4. Tower after two footings were lowered five feet by washout**

The special ground-wire strain clamp designed for this line has been satisfactory throughout the line.

### Towers and Footings

The satisfactory design of the towers and footings can best be indicated by a discussion of how these structures withstood the flood conditions that prevailed on March 2, 1938. Although one tower was lost, as has been indicated, there were many more at other locations that were in jeopardy and which with less liberal design, especially of footings, would have failed.

Floods in this area involve many short streams, normally carrying little or no water, which originate in the mountains, come down steep canyons, and in the case of the larger streams carry probably 50,000 cubic feet per second. The velocities even through the coastal plain are exceedingly high and very destructive. This flood was the worst in over 50 years. It was exceedingly widespread in its damage, affecting disastrously a large number of power lines, communication lines, railroads, highways, pipe lines, bridges, and many other important structures.

The tower that was undermined was in the wash area, but to one side of the established channel. The destructive power of the water can be judged from figure 1 showing a picture of the one remaining footing, with the tower visible approximately 200 feet downstream where it was carried by the force of the water. Obviously a failure of this kind put tremendous strains on the conductors and the adjacent suspension towers. In this failure the north ground-wire clamp broke free from the tower and the bottom conductor on the north side broke free at the bottom insulator. The other conductors were broken, by the pulls imposed by the falling tower.

The tower shown in figure 2, is immediately to the east of the tower that went out and shows that all arms and insulators remained intact. The insulators have a strength just under the broken wire pull that the cross arms can withstand. This tower received some help from a dead-end tower just beyond. On the west end, however, all the towers were suspension towers. The resulting strains on the conductor were such as to break insulator strings from one to three towers back depending on the conditions of pull. This is shown in figure 3. The towers were not damaged although they had to meet a duty approaching that on a strain tower. They are designed to withstand one broken conductor and one broken ground wire under maximum ice and wind conditions.

At another point in a rather indistinct water channel, a tower had all four footings completely exposed, and remained standing, due to the dead weight of the concrete footings. In another case, an angle tower, which was a considerable distance back from a water channel, had two of its footings undermined by the progressive cutting back of the bank. This tower is shown in figure 4. The footings were lowered about five feet but the weight of the footings prevented the tower from being pulled over by the transverse pull due to the angle.

These cases are representative of several others, where the sturdiness of the towers and the weight of the footings served to limit our outage to one location on the Boulder lines.

However, although this flood with its previously referred to widespread damage, did create a few points of danger and the actual loss of one tower, nevertheless to a very large degree the correctness of the location of the line and the placing of the structures is verified by the

# Symposium on Operation of the Boulder Dam Transmission Line—Corona Experience on Transmission Line

By BRADLEY COZZENS
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THE original basis for the selection of 1.4 inches as the diameter of the conductor for the Boulder Dam transmission line was provided principally by test data taken at the Ryan High Voltage Laboratory, at Stanford University, by the Department of Water and Power in co-operation with Doctor Joseph S. Carroll, on conductors ranging from 1.125 inches to 2 inches in diameter.[1] Also reference was made to other previous corona work at the same place.[2,3,4] An analysis and use of the data,[5,6] taking into account temperature and altitude effect and making some allowance for unknown factors affecting corona laws that had appeared in many of the tests, led to the final recommendation of 1.4 inches as the diameter for the conductor for 287.5 kv.

Cost curves for the line in terms of conductor diameter indicated that in the vicinity of minimum cost the curves were exceedingly flat, with about one per cent change from the minimum cost representing a diameter difference of 0.1 inch. Due to the peculiar shape of the corona loss curve, such economic choices would occur at the knee of the curve. However, the test work at Stanford had revealed that there were variations in corona loss that could not be accounted for by known temperature or barometric variations or other partially known factors such as humidity or surface conditions. The general indication was that after stable surface conditions had developed such factors would not cause a shift in the loss curve of more than ten per cent in voltage for the same loss. Realizing that if a conductor was operating near the knee of the curve and that this much shift in the loss curve of the conductor might run the losses tremendously and uneconomically high, it was decided to be somewhat liberal in selecting the conductor diameter. The excess diameter over that apparently required was taken as approximately 0.1 inch.

Tests on 1.65-inch-diameter hollow copper conductor of the segmental type, referred to as type *HH*, had indicated somewhat lower losses for that form of cable as compared with what would be expected from conductors with a stranded surface. It was believed, however, that a stranded cable of the diameter selected would be satisfactory for use on the line. Due to the small knowledge at the time on this subject of surface contour, no distinction was made for the difference in corona loss for these cables, in preparing specifications.

Later tests on various 1.4-inch-diameter cables, which were submitted by manufacturers in response to specifications, demonstrated the lower losses to be obtained with the smooth surface segmental type,[7] which was the conductor used on the line. This conductor also had economic advantage in that it could be made with the exact amount of copper necessary to carry the mechanical and electrical loading involved.

From the corona standpoint, the tests on 1.4-inch-diameter conductors indicated that any of them should be satisfactory, and that the 1.4-inch-diameter segmental-type conductor would be liberal as the losses were quite small, providing the surface conditions existing in the laboratory tests would be maintained in the field, by care in erection.

In addition to selecting a conductor size that would give low corona losses, a special effort was also made to design line hardware so as practically to eliminate unshielded corners or small radii that would be conducive to the formation of corona. The suspension clamp is essentially a box-shaped shell of smooth exterior with very liberal radii of curvature for all edges and corners. The strain clamps and connectors are designed so as to have rounded edges and dimensions that will make them corona free. In addition the use of $1^1/_2$-inch pipe for arcing horn structures at the high voltage end of insulator strings gives adequate shielding to hardware parts and the lower insulators to avoid corona formation at such points, as well as eliminating corona from the horn itself. In addition the long insulator strings used further reduced the duty on insulators to a point where corona formation at the insulators is practically eliminated unless disturbed by dirt and fog or other contamination.

## Noise Observations

### DRY WEATHER CORONA

After a line is in operation, a great deal of the judgment, concerning the performance of conductors with respect to corona, must be based on noise observation. This comes from the fact that, in a long line with low corona losses, it is very difficult to make any test arrangement whereby corona losses can be accurately determined. Such work involves not only the problems of accurate measurement of power at low power factor and high voltage, but involves subtraction of copper losses, affected by tem-

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[1] For all numbered references, see list at end of paper.

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tremendous percentage of the line that escaped without damage.

## Conclusion

The performance of other elements of the system will be discussed in appropriate papers associated in this symposium.

In conclusion it can be stated that the performance of the transmission line and its associated equipment has been satisfactory. The few difficulties that have been discussed are not to be regarded as materially detracting from the success of the line as a whole, but are mentioned so that the electrical industry might profit from a knowledge of their existence.

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## Discussion

For discussion see page 156.

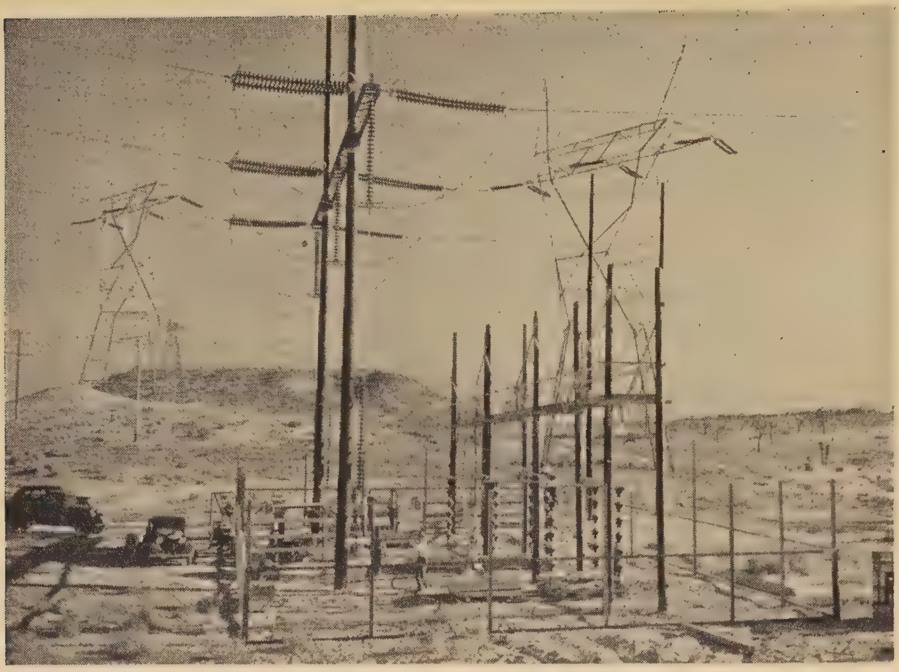

**Figure 1. The test line and high-voltage wattmeter arrangements for Victorville corona tests**

The steel towers in the background are part of the main transmission lines

perature at various points and the variation in the charging current along the line. In order to maintain proper voltages at each end of the line, in accordance with those existing during normal operation, synchronous condenser operation is necessary and determination of such losses must also be made. The interpretation of the results is also difficult due to the variation in elevation and temperature along the line.

When 90 miles of the line was first energized from the Los Angeles end, observations taken near the receiving station indicated a corona noise of moderate intensity that could be heard for a distance of approximately 400 feet. This statement means that such noise is at the threshold of hearing at that distance when observed by a person accustomed to listening to corona noise and who is concentrating his attention on its observation. Newly energized circuits generally have a higher noise level than found on the same circuit after weathering. After this conductor had weathered for the month or so until normal operation was in effect, and then further weathered for about two months with voltage applied, the noise as observed for dry weather was very much reduced and became essentially inaudible when observed from the ground when standing directly under the line midspan. In general, in the vicinity of Los Angeles, it is only under exceptional conditions that the dry weather corona noise becomes audible when so observed. Under such conditions noise can develop very suddenly and apparently with no observable change in temperature or humidity or known factors affecting corona loss. It would be of an intensity that becomes inaudible at about 200 feet, and is not of long duration and is less noisy than tire noise from an automobile traveling on smooth pavement.

In the foothill region east of Los Angeles where the line is at elevations of approximately 2,000 feet, the dry-weather noise is not much different from that which has been discussed. It can probably best be described by saying that an occasional corona brush manifests itself with an intermittent buzzing sound.

When observations are made in the mountains and desert, inconsistencies begin to appear. The highest noise levels are not found at the high elevations as would naturally be expected from the variation of the air density factor. Observations at elevations in excess of 4,500 feet are usually inaudible if the location is such that the observer cannot be close to the midspan because of a gulley or canyon. The audibility at the tower due to approximately 100 feet elevation of the conductor is quite low. At other points of high elevation where the contour of the ground permits observation at closer distances, a mild corona noise is heard.

One of the few sections producing the most noise is in the vicinity of mile 175 from Boulder at an elevation of 3,200 feet. When at its highest level the noise at this point has the crackling sound associated with a small grass fire and also a low humming sound similar in quality to transformer hum, is sometimes heard. When the noise is at its maximum, at this location, it becomes inaudible at a distance of 1,200 to 1,500 feet. This noisy location exists for a distance of about three miles on both circuits. There is considerable variation in the noise from day to day, over and above that due to temperature changes. A high degree of noise has been observed on cool evenings and very quiet operation has been observed during warmer daytime periods, which is contrary to normal expectations. Sometimes in the course of a few minutes a conductor will exhibit alternations of noise and quietness.

At night, no uniform envelope of corona is visible, as the discharge is in the form of scattered and intermittent brushes from two to eight feet apart, which are visible at midspan where the conductor is about 30 feet above the ground.

There has been occasion to notice about four other similar areas where such corona conditions exist but probably to a lesser degree.

During wind storms, in the desert, other lower voltage lines had been observed to have a glow similar to corona, probably due to charging or discharging dust particles or other atmospheric charge phenomena. On the assumption that atmospheric charges might have some influence on corona loss and noise, an observation station was set up in the vicinity of mile 175. At two locations, about 800 feet and $1^1/_2$ miles from the line, antennas about 50 feet long were carried on masts 30 to 40 feet above the ground on hilltop locations. An electroscope was used to measure the potential of the antennas to ground. Arrangements were also made adjacent to the line to measure radio interference noise, and to record audible corona. By taking observations simultaneously at both places, it was thought it might be possible to obtain some correlation between atmospheric charges and corona noise. Voltages up to approximately 2,000 volts were measured by means of the electroscope, which is not uncommon for antennas in the desert. Very little if any correlation was observed between the accumulation of charges on the antennas and noise on the transmission line.

For the great part of the line length, corona noise is at a comparatively low level. At elevations of the order of 2,300 to 2,700 feet, which is about the average elevation of the line, and on a normal dry day with the temperature a little above average, the noise is at the threshold of audibility at a point midway between the two single circuits, which have a separation of 265 feet. This general low level of corona noise is very satisfactory and indicates that the conductor design has been adequate.

WET WEATHER CORONA

As soon as rain begins to fall on the conductor, corona noise becomes evident at any location. The noise is so directly coincident with the beginning of the falling of the drops, that the cause of the loss and noise is either the exchange of charges between drops and the conductor or the mechanical pattern and shape of conducting water caused by the rain drops striking the conductor. The motion of the drops in the alternating electrostatic field may also contribute to the humming sound quite evident during rain. The resulting noise is moderate.

At an elevation of 1,000 feet, where adequate darkness prevails, it is just barely possible to see rather intermittently the bluish corona glow during rain. At elevations in excess of 2,000 or 2,500 feet, and similar darkness, the faint blue glow of corona is visible for about two spans. The glow frequently has an intermittency that gives the effect of longitudinal motion along the conductor. It is believed that this effect may be due to rain drops hanging along the bottom of the conductor, when it is vibrating slightly. Then the drops are either shaken loose or elongated by the motion, which develops glow either by changing the gradient, or by carrying small charging currents to the falling drops.

## Desert Loss Measurements

For the past several months consideration has been given to the design of a third 287.5-kv Boulder circuit. Due to the fact that no high-voltage source was easily available for testing in the actual line location heretofore, the work had all been done at the Ryan laboratory. On the basis of such tests, 1.4-inch-diameter stranded conductor was considered to be satisfactory for 287.5-kv operation and 1.4-inch-diameter hollow copper conductor of the segmental type showed appreciable liberality. These facts together with a general excellence of performance of the 1.4-inch conductor being used, brought about the suggestion that the possibility of using a smaller diameter of conductor be investigated. However, observations of noise at some special locations on the desert, as previously mentioned, indicated some departure from the laboratory conditions and made it desirable to have some loss tests made actually under desert operating conditions.

Since high voltage was now available from the Boulder circuit, a test set up could be made at the Victorville switching station. By isolating the portion of one circuit from Boulder to Victorville and supplying it from one generator, voltage could be controlled from any desired low value up to about 360,000 volts at Victorville. High-voltage wattmeter equipment similar to that used for some of the tests at the Ryan laboratory,[8] and a suitable test line, were erected. General views of these test arrangements and their location with respect to the switching station are given in figure 1 and figure 2.

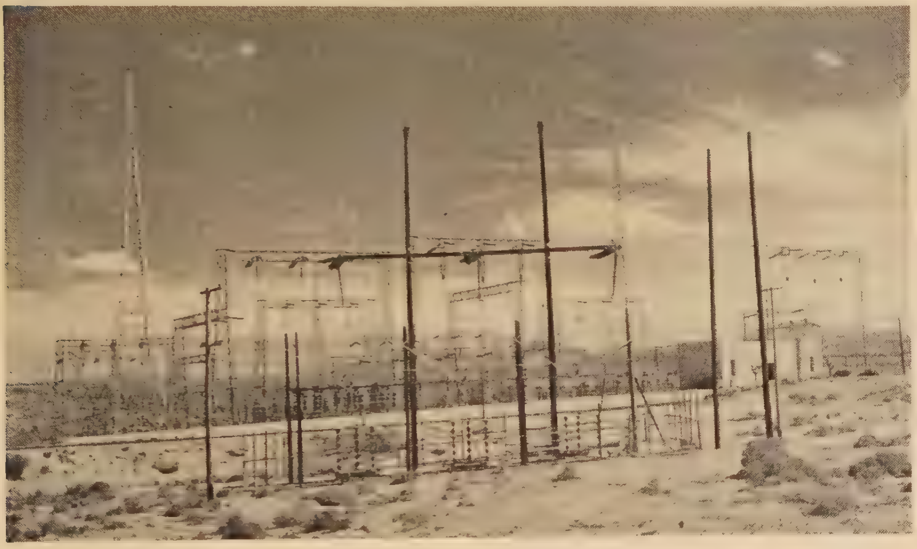

**Figure 2. High-voltage wattmeter equipment for the Victorville corona tests**

The steel structure in the background is the Victorville switching station

At this location, tests are in progress on 1.25-inch-diameter and 1.4-inch-diameter hollow copper type *HH* conductor and also on some 1.4-inch stranded aluminum conductor steel reinforced that had been tested previously at the Ryan laboratory. At the conclusion of this work, the details will be reported.

One important result of these tests was that, after due allowances had been made for barometric pressure and temperature, it was found that the losses at Victorville were appreciably higher than those obtained at the Ryan laboratory. This is true for all conductors tested to date, including stranded as well as those of the segmental type. The aluminum cable is the identical sample tested at Stanford and its surface was carefully protected so as not to be roughened or damaged in shipment or erection. The 1.4-inch type *HH* cable was a fair sample of that cable, not noticeably different to any that had been heretofore tested or used on the line. The 1.25-inch diameter type *HH* cable was a new size manufactured for the test, but the equivalent of its losses at Stanford can be judged from interpolations made from tests on 1.1-inch and 1.4-inch-diameter cable.

The increased corona losses measured at the Victorville test location are sufficiently higher than those obtained at the Ryan laboratory, so that the difference cannot be explained on the basis of any reasonable altitude and temperature corrections. The losses are also sufficiently high so as to make unattractive the use of 1.25-inch-diameter hollow copper conductor of the segmental type or even 1.4-inch-diameter conductors with a stranded cable surface. As far as can be judged by measurements to date, which are not fully completed, 1.4-inch-diameter hollow conductor of the segmental type as used on the line will have losses sufficiently low as to confirm the design and size of this conductor as being satisfactory for 287.5-kv lines.

Such higher losses have been found on clear days and under such conditions that wind, humidity, temperature, and barometric pressure do not offer sufficient explanation for the results. The conductors have been tested as soon after washing as was possible, without demonstrating that the accumulated contamination of the conductors was increasing the losses. Among the intangible items that have been mentioned as possible causes are such things as atmospheric charges, sun-spot phenomena, invisible charged dust particles, the presence of radioactive materials in the vicinity or as dust on the conductor, or the presence on the conductor of any chemicals that may increase the emission of electrons. A new field of corona investigation is thus opened up.

As a final check on corona loss on the Boulder transmission line, reference should be made to the over-all monthly efficiencies that are given in table I, of the companion paper on general operation of the transmission lines. These losses agree so closely with calculated resistance and equipment losses, that the corona loss is negligible.

## Conclusion

The experience obtained to date in the operation of the line indicates a general low level of audible corona noise and conservative corona losses thus substantiating the original design.

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## Discussion

For discussion see page 156.

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# Symposium on Operation of the Boulder Dam Transmission Line—Insulation and Lightning Protection

By BRADLEY COZZENS
MEMBER AIEE

**Synopsis:** This paper covers a résumé of the fundamental principles of insulation and lightning design for the Boulder Dam transmission line, including the fog problems encountered in the coastal regions and the lightning problems of the desert section. The operation in both areas is covered, with particular reference to the lightning encountered during two years of construction and one year of operation. A description of the lightning recording equipment with current values and frequency of strokes is reported. From these values the adequacy of the design is definitely indicated.

THE Boulder Dam-Los Angeles transmission system of the Bureau of Power and Light traverses country presenting a wide variation in geological and climatological conditions. Starting from practically sea-level conditions at the Los Angeles terminus, the line passes through low-lying alluvial valleys, with their accompanying fogs, through the foothill sections and across the gravelly and rocky talus slopes at the base of the San Gabriel Mountains. Passing over Cajon Pass at an elevation of 4,415 feet, the line drops gradually into the Mojave Desert area for the remainder of the 190 miles to the Boulder power plant. For those unfamiliar with this territory, it is a mingling of mountain ranges, large sloping valleys of a generally rocky character with occasional sinks or dry lakes that are flooded at two- to four-year intervals by desert storms. In this section the line varies in elevation from 800 to 4,862 feet with the general trend being between 2,000 and 3,000 feet. The average rainfall in this territory is between one and six inches per year which usually comes in one or two storms of cloudburst proportions.

In the area between the Cajon Pass and the coast the line is subject to long dry periods during the summer months, at which time the insulators collect considerable dust aggravated by field cultivation. This period is followed by the heavy fogs, in the fall of the year, which fogs come without much warning and seriously impair the effectiveness of any insulation. Although in the desert area there is appreciable dust, there is almost complete freedom from fogs and its attendant problems. The rains come as heavy downpours that serve primarily to wash insulation rather than producing any insulation problem from this standpoint.

The familiar isokeraunic charts presented by the United States Weather Bureau[1] show Los Angeles having less than 5 lightning storm days per year; the mountainous section between Los Angeles and the desert, approximately 7; with the frequency gradually increasing to approximately 30 in the vicinity of Boulder Dam. Prior to the design of the line, these values were partially substantiated by a survey of the territory and of the operating records of the few transmission and telephone lines that traverse it.

Thus two definite insulation problems were presented; namely, insulation for the lightning voltages of the desert and insulation to be free from flashover due to dust and the fogs of the coastal region. Since the system was to be a major source of supply for the City of Los Angeles, justifying the high degree of reliability specified by the management, the design contemplated practical immunity from flashover from either lightning or insulator contamination and fog.

## Fog Design

Insulation that will withstand contamination and wetting of fog has been a baffling problem on the Pacific Coast for many years. Studies made in connection with the design of the Boulder Dam line and other lines of the Department gave a good understanding of the action of insulators under these conditions and also led to the redesign of lightning arresters[2] to operate under such conditions. Under fog conditions the leakage current over insulators is 20 to 200 times the normal capacitance current. The voltage distribution is thus determined by surface resistance alone.

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[1] For all numbered references, see list at end of paper.

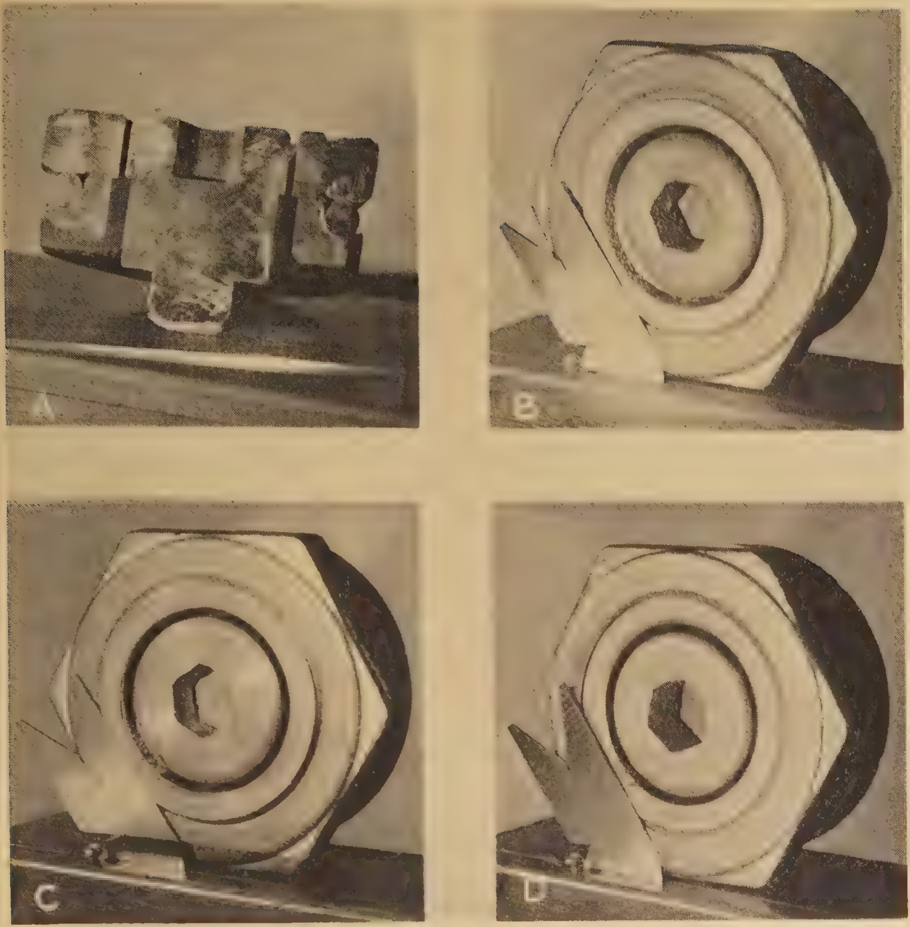


**Figure 1. Gaps used to fasten counterpoise to tower leg and to break the electrolytic circuit between copper counterpoise wire and zinc-steel tower legs**

A—Section through gap, stud cut off
B—Gap flashed by natural lightning
C—Gap flashed in laboratory, 75,000 amperes
D—Gap flashed by natural lightning

Since the drying of the surface film increases its resistance and consequently the voltage duty and power dissipated in the dry areas, these drier sections will continue to heat and dry carrying more voltage duty while the other areas become wetter and take less and less voltage duty. The caps of these drier units may operate in excess of 35 degrees Fahrenheit above the ambient air temperature, while the high-resistance area adjacent to the pin may be much hotter.

The results of the fog tests on practically all commercial and many special insulator shapes showed the old-type 12-inch flat disk to have the lowest leakage current and ability to insulate in fog. Though the smooth surface and poor electrostatic stress distribution of this type unit inhibits dust deposition, the same conditions exaggerate the sparking and arcing of the wet units eliminating its use in populated areas. However, this unit has approximately 20 per cent lower impulse flashover than the conventional-type insulators which eliminated its use in other locations. Little, if any, improvement was found for any of the so-called fog-type insulators available for these tests. To facilitate cleaning and yet obtain the greatest leakage in a given string length, the ten-inch-diameter five-inch-spaced standard suspension disk was selected for this type of service. In accordance with tests and the successful operation of 20 such units on 220 kv in northern California it was felt that the use of 24 units at the higher voltage but somewhat less severe fog condition on the Boulder Dam lines would preclude the possibility of flashover for a number of years. To prevent disturbance in the residential section through which the line passes a program of washing the insulators once or twice a year

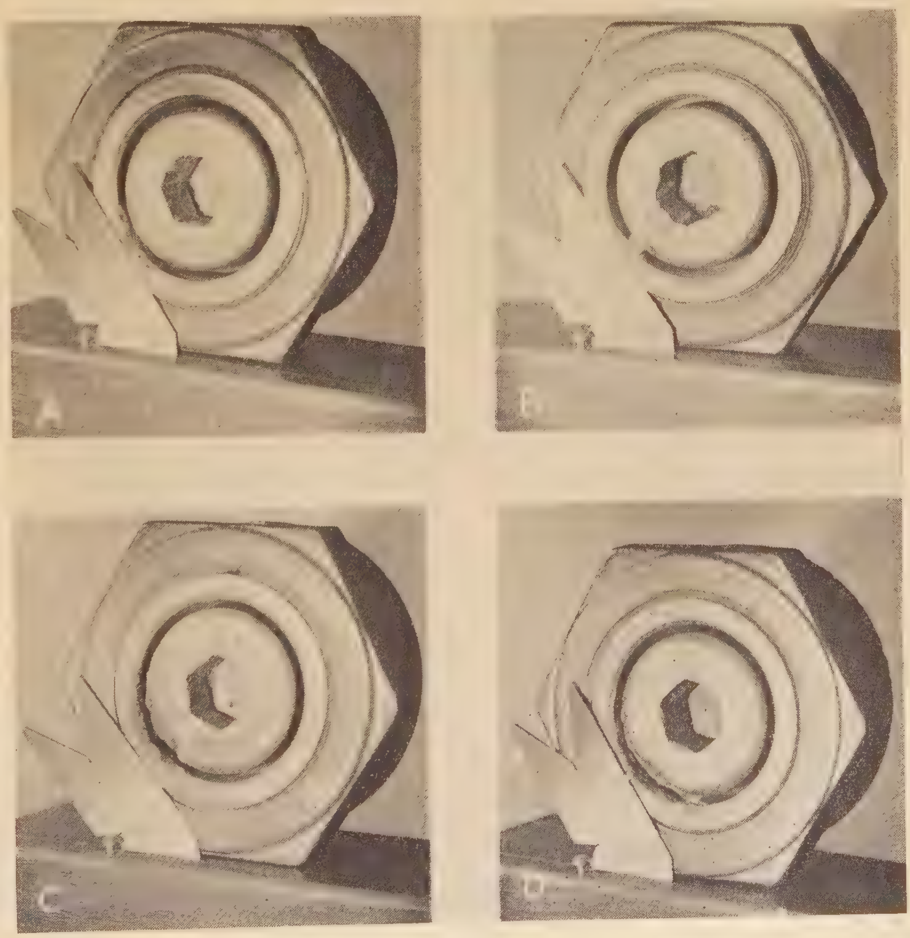
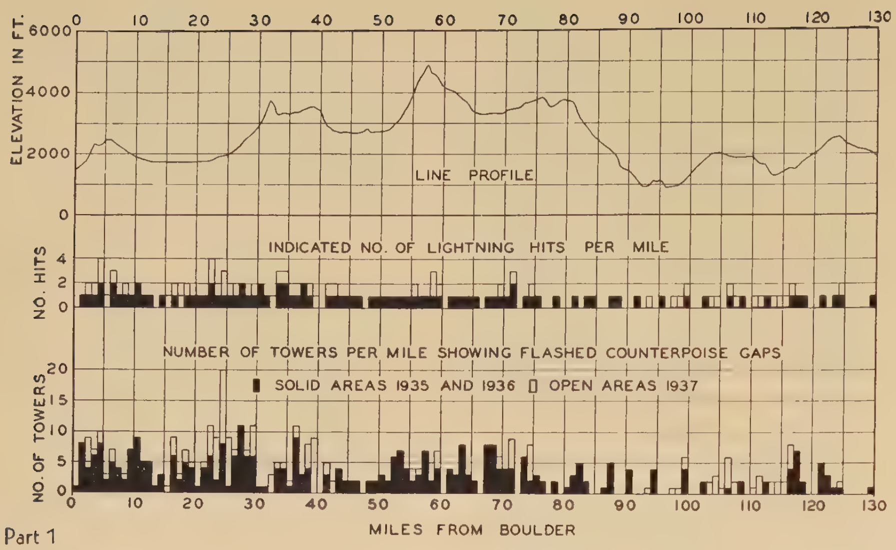


**Figure 2. Gaps used to fasten counterpoise to tower leg**

A—Gap from same tower as gap of figure 1 D. Note multiplicity of burns
B—Gap fused across by natural lightning
C and D—These gaps resemble power-frequency burns and appear to be the result of many strokes. Gaps burned before line was energized



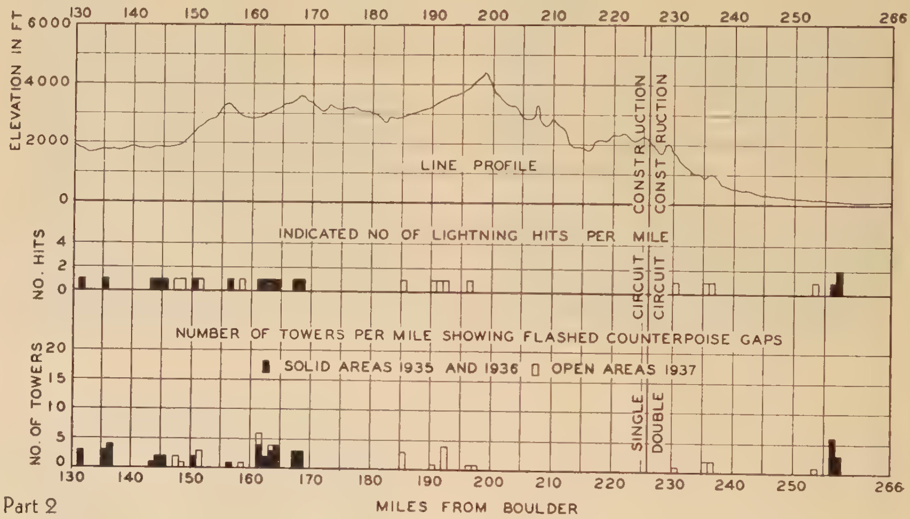


**Figure 3. Parts 1 and 2, graphical presentation of lightning strokes per mile and number of towers affected per mile as indicated by flashed counterpoise gaps with accompanying profile of tower footing elevations**

with high-pressure jets is being used. A section of the line approximately five miles long has been washed twice to date in this manner.

At Victorville switching station, less than a mile from a large cement plant, the station insulation, switch supports, and housings are washed frequently to prevent setting of the cement dust. Jet pressures up to 800 pounds per square inch are used. The line for a distance of about ten miles through this territory is washed once a year. It is contemplated that cleaning the insulators on the remainder of the line will be unnecessary.

During the 20 months of operation of the Boulder Dam circuits involving practically two complete fog seasons, there has been no danger of flashover in the fog areas, and with the washing program being followed, the noise created by the insulators under fog conditions is actually less than that existing on the lower-voltage lines.

## Lightning Design

At the time the lightning design of the Boulder Dam line was started, lightning theory had not been developed nearly so far as at present. Direct hit theory[3,4] had a few proponents and had had its first substantiation by reasonable methods of calculation.[4,5] Counterpoise had been used successfully in one location[6] and before the erection of the line had been installed on other transmission systems.[7,8] Many of the factors used were not contemplated in the mathematical theory of lightning phenomena at that time; such as, change in stroke surge impedance with voltage, change in coupling factor due to excess voltage and corona, reduction in kilovolts per foot values for long distance flashovers, the concentration of charge on the ground surface rather than at the equivalent ground plane depth, the effect of current leaving the towers in opposite directions in reducing the surge impedance, and many other factors.

In general, classical wave theory as applied to transmission lines[4,5,9] was used as the main basis of design. The voltages encountered were based on 16 to 20 million volts in the streamer at the tower top. The streamer surge impedance used was the conventional 200-ohm value, though studies were made with other values as modified by size of corona sheath and height above ground. This variation in streamer impedance as well as the impedance of the feeder streamers or collecting paths within the cloud are considered extremely important factors in determining the current in the lightning discharge. The flashover voltages for the longer distances were extrapolated from existing curves with the slope slightly decreased in the upper regions. The theoretical corona sheath diameter was used for the capacitance element in computing coupling factors and surge impedance while the metallic conductor diameter was used for the inductive component. In the case of towers, due to the already large dimensions, physical dimensions only were used for both the inductance and capacitance elements. There is appreciable reduction in theoretical surge impedance for the case of wires leaving a junction in opposite directions. Though this effect decreases rapidly with distance, it is believed that this effect combined with the fact that the charges are located on or near the ground surface accounts for the improved performance of the counterpoise ground over the vertical ground well, even though the latter may have the lower measured resistance.

As contemplated, ground resistance measured on stakes driven to approximate counterpoise depth showed resistance values as high as 3,000 ohms, though the large concrete tower footings at their greater depth showed values from as low as one ohm up to 150 ohms, with the majority of the footings measured showing less than 10 ohms. It was realized that to attempt to terminate counterpoise wires in this high-resistance top soil layer would produce severe voltage reflections and render the counterpoise ineffective. In addition, with the equipment developed for laying the counterpoise, it was more economical in most cases to use the additional length of wire in laying a continuous counterpoise than it would have been to attempt to cut and ground radial wires at the end of shorter runs. The continuous counterpoise was used, each wire leaving the tower radially until 135 feet apart, then turning to run parallel to the center line of the transmission circuit, thus gaining the advantage of low surge impedance of the radial counterpoise without the disadvantages of terminal reflections. In the desert section where the two single-circuit tower lines are used, there is a cross tie between the adjacent counterpoise systems of the individual circuits. This gave a theoretically lower surge impedance than would have resulted from the addition of a single wire, but with approximately a one-microsecond time delay. Arrangement of the counterpoise was given in a previous paper.[10]

The evaluation of the counterpoise surge impedance is still a debatable matter. In this design attempt was made to duplicate by calculation values that had been recorded in tests.[11] It was necessary to use correction factors to get agreement between these data and computed values, though some writers later obtained agreement by the use of two-wave theory.[12] The correction was primarily the use of a slight corona sheath or high-conductivity area in the ground and surrounding the counterpoise. That this condition exists can be indicated by surging a conductor in water of high conductivity and observing the corona formation on the conductor under the water. The other factor, primarily not a correction, was the use of a dielectric constant greater than unity for the material outside of this corona envelope. With these corrections, close agreement between theory and measured values was obtained.

Realizing the possible inaccuracy of the assumptions upon which lightning theory is based, a slight safety factor was considered desirable. The curve of flashover with ten-microsecond time lag lies approximately 12 per cent below the same curve for two-microsecond time lag. To introduce a safety factor, the curves for the ten-microsecond time lag were used for insulators and gaps, rather than the two-microsecond values as computed. Thus if the computed values were rigidly correct, the use of the ten-microsecond curves would give a 12-per cent overinsulation for the maximum lightning voltages expected, which percentage is no more than the erraticness of flashover voltage.

On the basis of these studies a 16- to 20-million-volt lightning stroke to the tower would require approximately ten feet of insulation to prevent flashover. To balance this insulation for the case of a stroke to the ground wire at the center of a 1,000- to 1,200-foot span would require a separation of 40 feet between ground wire and conductor at mid span. This balance of insulation between the supports at the tower and the separation between conductor and ground wire at mid span has been substantiated by recent literature.[13]

## Insulators

A lightning generator of the cage type was erected at the Harris J. Ryan High Voltage Laboratory, Stanford University, and with the co-operation of Doctor J. S. Carroll, studies of the effect on impulse and 60-cycle flashover of insulator separation, diameter, and shape were made on practically all commercial shapes available at the time. Assemblies up to ten feet in length were tested. Other data[14] published by eastern laboratories substantiated these measurements and furnished additional data upon which to base cost studies. This study included, in addition to the cost of insulators, the cost of added tower height and cross-arm length necessary to maintain the same flashover voltage. On this basis, the 10-inch-diameter 5-inch-spaced unit showed a decided economic advantage, while the 12-inch-diameter conventionally shaped unit with a separation of $5^3/_4$ inches showed the second lowest cost based on insulator and steel prices at the time of the study. Because of these studies, the 10-inch-diameter 5-inch-spaced insulator was selected for the desert or lightning section as well as fog section of the Boulder Dam line.

## Grading Rings

Initial studies were made on a relatively large oval grading ring for the lower end of the insulator strings with a circular ring for the top end of the assembly, and their proper dimensioning and location was verified by impulse tests in the laboratory of one of the eastern manufacturers. These shields proved too costly for the improvement offered; so it was decided to use a relatively large arcing horn at the lower end of the string with a strap-type upper horn. The basis of design and positioning of these arcing horns was such that they should prevent cascading for all string flashovers occurring in three microseconds or less, and be free from corona at a voltage 20 per cent above the operating voltage. This basis was followed as an insulation standard for all of the equipment on the Boulder Dam lines. The insulator assembly has been pictured in a previous paper.[10]

## Operation and Measurements

One of the circuits was first energized for its entire length from Boulder power plant on October 9, 1936, and went into permanent operation on October 26, 1936, as described in a companion paper.[15] Thus the energized line was subjected to a few storms at the end of the 1936 lightning season and all of the 1937 season under normal operating voltage.

The line erection was started in the latter part of 1934, and approximately 27 per cent of the overhead ground wire and a somewhat larger percentage of the counterpoise had been installed by August of that year. During the 1935 lightning season, 73 per cent of the ground wire and 79 per cent of the counterpoise were installed with conductor stringing progressing to about these same values. Thus in the collection of data, the 1934 and 1935 season are considered as one year and called 100 per cent line length. The line was 100 per cent complete during practically all of the 1936 lightning season.

The counterpoise leaving the base of the tower is attached with a gap connection for the purpose of preventing electrolytic corrosion between the copper counterpoise and the zinc and steel of the tower leg. External from the tower, however, the counterpoise is continuous with the loop between the two wires of each circuit and between adjacent circuits closed at each tower to prevent building up excessive induced potentials in long isolated leads. A cross section of one of these gaps with the counterpoise wire in place is shown in *A* of figure 1. The gap is of cast bronze with molded bakelite insulation between the two elements and bolts directly to the tower leg about seven inches above the footing. The gap between the concentric cylindrical elements is $^1/_{16}$ inch, which offers no barrier to lightning voltages.

In addition to providing the insulation necessary to break the zinc-copper circuit, the counterpoise gaps serve to indicate the location of lightning strokes. The first indication of outstanding importance from these gaps was an observed direct hit which involved the gaps on seven towers of the two adjacent circuits. From the nature of the burns a code was developed primarily involving burn size and location and the nature of the burn. The diameter or size of the burn was given as a number indicating twentieths of an inch; thus, a half-inch burn is a number 10 burn. Early in 1937 the gaps on the first 200 miles from Boulder were surveyed. This survey, covering the two years of erection with a few months of operation, revealed a wide variety of burns ranging from a small bead of copper about 0.02 inches in diameter to burned areas covering over one-half inch of the circumference of the gap. Other discharges fused the gap together in diameters in excess of $^1/_8$ inch. The code that had been developed was inadequate and had to be revised, though the measurement of the burn diameter in twentieths of an inch was retained.

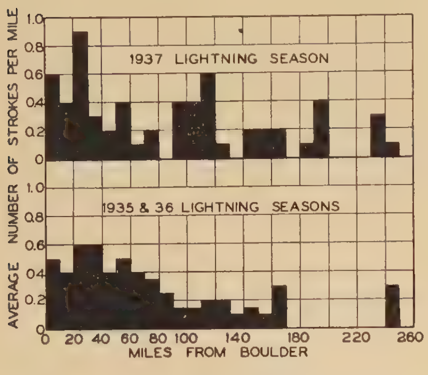


**Figure 4. Average number of lightning strokes per mile per year. Averages obtained for each ten mile section**

At about this time published data indicated that burn size could be used as an indication of the magnitude of crest current.[12,16] The sponsor of this idea checked this effect on the counterpoise gaps using an oscillatory wave and currents from 25,000 to 100,000 amperes. The burn diameter was found to be proportional to current with approximately 0.625 inches of burn per 100,000 amperes. These burns had the character of molten metal that had been blown violently. The burn as produced by test with 75,000 amperes is shown in figure 1 *C* and is about $^9/_{20}$ inch in diameter. The burns produced by actual lightning are equal or greater in diameter than those obtained in the laboratory. Figure 1 *B* shows a burn from natural lightning of the same character as the laboratory burn that is between $^{12}/_{20}$ and $^{14}/_{20}$ inch in diameter. This would indicate a current in excess of 100,000 amperes. Figure 1 *D* shows another burn of the same nature between $^4/_{20}$ and $^5/_{20}$ inch in diameter that was obtained from a tower leg on which the magnetic-link-type surge-crest ammeter had recorded 21,000 amperes with 18.5 per cent oscillation. The magnetic links on the north leg of the same tower indicated a similar current value, but the gap showed three or more burned areas indicating the multiplicity of the strokes. The diameter of the individual burns was approximately $^3/_{20}$ inch while the laboratory data would have indicated 21,000 amperes should have burned an area between $^2/_{20}$ and $^3/_{20}$ inch.

Complete fusing of the gap occurred in only about five cases. Figure 2 *B* shows a typical case in which the diameter of the fused section is nearly $^3/_{20}$ inch. This condition is considered to be the result of many low-current strokes of a multiple discharge, or the result of a low-current long-time discharge. Figures 2 *C* and 2 *D* show two burns of a similar nature, yet much more extensive. These are assumed to be the result of multiple strokes or many strokes in the same location. These latter burns have the nature of power-frequency burns, but there have been no flashovers since the line was energized, so they are known to have been the result of lightning.

Though there is close agreement between the laboratory and field data in many cases, others show little similarity. Extreme care and considerable more data will be necessary before using the counterpoise gaps as an accurate current-measuring device, primarily because of the multiple nature of the lightning discharges with overlapping burns, the oscillation between the streamer and the lightning-protection system or within the latter, and the great variation in the time of discharge, though at present duration of discharge is considered to have little effect on diameter. Further calibration data are being obtained and it is hoped that future reports will include current values as indicated by the counterpoise gaps.

The location of the counterpoise gaps flashed by lightning is given diagrammatically in figure 3. The line profile is included in the charts. The data from the survey of May 1937 include all of the gaps that were flashed during the 1935 and 1936 seasons except those changed by construction crews and are indicated by the solid areas. The data from the survey of May 1938, covering the 1937 lightning season, are indicated by the open areas of the chart.

The upper section of the chart shows a great many more gaps flashed in the first 130 miles from Boulder Dam than in the lower section of the chart which covers the remainder of the line. This substantiates the data given by the Weather Bureau's isokeraunic charts.[1] There was a total of 110 strokes indicated during the 1935 and 1936 seasons, or an average of 55 per year, and 63 during the 1937 season. In general, less towers were involved per stroke during the 1937 season than during the previous seasons, due possibly to inaccuracies of the earlier survey or overlapping of the two seasons. With but few exceptions, the lightning is relatively evenly distributed in the first 80 miles from Boulder Dam. The lack of hits at the high point of the line in mile 32 is due to the fact that the line runs through a pass and is protected by adjacent mountains. This is also true to a lesser degree of the ridge in mile 39 and 40. For the next 30 miles, from mile 40 to 70, the 1935 and 1936 seasons showed little decrease in intensity, but the hits during the 1937 season were very scattered, being limited to sections adjacent to the high points. It was this summit at mile 57 that showed the heavy power-frequency type burns of figures 2 *C* and 2 *D* during the 1936 season. The section between mile 80 and 170 shows a decidedly lower lightning level with a still lower lightning level between mile 170 and the Los Angeles terminal of the line.

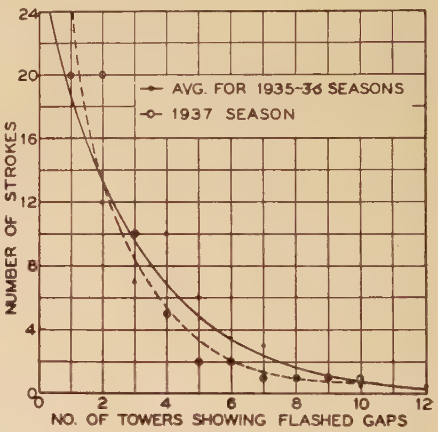


**Figure 5. Variation in lightning stroke intensity as indicated by the number of strokes affecting various numbers of towers—indication obtained from flashed counterpoise gaps**

The group of hits near mile 257 indicated as a 1936 hit occurred in December 1936 after the line was energized. This was in the section of double-circuit construction where the lightning protection is less effective than in the single-circuit area, due to less counterpoise and greater separation between the ground wire and lower phase wires. There was no flashover, yet the counterpoise gap burns on two adjacent towers indicated in excess of 100,000 amperes per tower.

Figure 4 gives a condensed indication of the lightning stroke intensity throughout the line. The values plotted are the average strokes per mile per year for the ten-mile section included. The lower section using two years data shows a general trend with the number of strokes decreasing between the dam and Los Angeles. The upper section for 1937 only is very erratic in nature. There are high sections between miles 90 and 120, 140 and 170, 180 and 200, and again between miles 230 and 250. These blocks were not shown clearly by the larger plot of figure 3.

In the lower section of figure 3 is shown the number of towers per mile that showed flashed counterpoise gaps, which follows the same trend as the number of hits per mile. The duplication of hits in mile 24 produced an unusual quantity of flashed gaps yet the whole section of the line up to mile 80 showed a large number of flashed gaps. In addition to showing the lightning frequency decreasing west of mile 80, figure 3 also indicates that the intensity may be decreasing also due to the smaller number of flashed gaps for each hit. There are many more hits in this section where only one or two towers are affected.

As an indication of the distribution of stroke intensity, figure 5 shows the number of strokes that flashed counterpoise gaps on various numbers of towers from 1 to 12. The plotted dots and solid-line curve give the approximate average per year for the 1935 and 1936 seasons combined, while the plotted circles and dash-line curve cover the 1937 season. The two average curves are surprisingly close together though the individual points are erratic. From the curves it is seen that between 12 and 20 lightning strokes per year will involve but 1 or 2 towers; 4 per year, 4 towers; 2 per year, 6 and 7 towers; and a stroke every other year, or half a stroke per year, may involve 12 towers. There are, of course, those discharges that will not permanently mark the counterpoise gaps. Artificial lightning discharges of approximately 4,000 amperes show only slight discoloration with no pitting of the metal. This type discharge soon oxidizes and any record from it is lost; so that many more gaps are flashed than are actually found in the gap survey.

The number of strokes indicated may be in slight error due to some hits that were multiple in character, terminating successively on both towers yet recorded as one hit only. This increases the number of gaps per stroke, for some of the gaps flashed on the second circuit were probably due to cross currents from the preceding stroke on the other circuit and vice versa. These are located in some cases by the displacement of the center of disturbance on the two lines, showing how easily both circuits may be involved in open country even though 265 feet apart.

Magnetic-link-type surge-crest ammeters are installed on 23 miles of the Boulder north circuit including miles 1 to 12 and 22 to 32. Recorders are installed also on all diverter towers at the Boulder switch rack and Silver Lake and Victorville switching stations. The normal location of the supporting bracket is seven feet above the top of the concrete footing which is three feet below the first panel point. Where unequal leg extensions or irregular tower construction is involved, the supporting brackets are placed at a symmetrical point in the tower. In the normal installation there are two brace angles, $2^{1}/_{2}$ by 2 by $^{3}/_{16}$ inches that terminate seven feet below the link brackets. The leg members are 5 by 5 by $^{5}/_{8}$ inches so it is anticipated that the major portion of the current is carried by these leg members. From the inspection of the counterpoise gaps prior to the installation of the magnetic links stroke currents of over 200,000 amperes per tower were indicated. Since with the insulation level on these lines low-current strokes could not cause flashover, and to record more accurately the high current strokes, the magnetic links were located 6 and 18 inches from the center of gravity of the angle rather than the 3 and 9 inches as in the normal installation.

**Table I. Magnetic-Link-Surge-Crest-Ammeter Data for 1937 Lightning Season**

| Tower Number | Stroke Number | Leg | Current | Per Cent Oscillation | Cloud Polarity |
|---|---|---|---|---|---|
| 25-*N*-3 | 37–1 | N | *2,800+ | over 50 | – |
| | | E | 8,400 | 50 | – |
| | | S | 4,400 | – | – |
| | | W | 2,000 | – | – |
| | | | 17,600 | | |
| 25-*N*-4 | 37–1 | N | 21,150 | 18 | – |
| | | E | 20,600 | 18.5 | – |
| | | S | 23,300 | 19.5 | – |
| | | W | 19,150 | 21.5 | – |
| | | | 84,200 | | |
| 25-*N*-5 | 37–1 | N | *3,000 ± | over 50 | – |
| | | E | Trace | – | – |
| | | S | 5,000 | – | + |
| | | W | 3,000+ | over 50 | – |
| | | | 6,000 | | – |
| | | | 5,000 | | + |
| 26-*N*-1 | 37–1 | N | Trace | | – |
| | | E | Trace | | – |
| | | S | *2,000 ± | over 50 | – |
| | | W | Trace | | – |
| 26-*N*-5 | 37–2 | N | 8,200 | 50 ± | – |
| | | E | 9,800 | 50 ± | – |
| | | S | 3,800 | – ± | – |
| | | W | 3,600 | – ± | – |
| | | | 25,400 | | |
| 4-*N*-3 | 37–3 | N | 10,600 | 50 ± | – |
| | | E | 9,000 | 50 ± | – |
| | | S | 5,300 | 50 ± | – |
| | | W | 10,400 | 50 ± | – |
| | | | 35,300 | | |
| 22-*N*-6 | 37–4 | N | *2,000 | – | – |
| | | E | 1,600 | – | – |
| | | S | 2,000 | – | – |
| | | W | 2,400 | – | – |
| | | | 8,000 | | |
| 23-*N*-1 | 37–4 | N | 13,400 | 32 | – |
| | | E | 15,400 | 37 | – |
| | | S | 16,800 | 29 | – |
| | | W | 17,100 | 28 | – |
| | | | 62,700 | | |
| 24-*N*-5 | 37–5 | N | 15,000 | 35 | – |
| | | E | 14,000 | 44.5 | – |
| | | S | 13,200 | 42 | – |
| | | W | 13,200 | 47 | – |
| | | | 55,400 | | |
| 25-*N*-1 | 37–5 | N | *5,000 | over 50 | – |
| | | E | 4,000 | over 50 | – |
| | | S | 4,000 | over 50 | – |
| | | W | 2,000 | over 50 | – |
| | | | 15,000 | | |

* Approximate.

In addition to the above mentioned installations, magnetic-link type and paper-film type surge-crest ammeters are installed on the 12 lightning-arrester phase units at the Boulder end and the six phase units at the Los Angeles end of the circuits. To date there have been no discharges recorded by the links on the arresters, though the paper film gaps on two of the arresters at Boulder showed very small punctures, possibly due to overvoltages combined with switching surges.

Five strokes have occurred of sufficient magnitude to record accurately on the magnetic links as located. One of these strokes showed indication on four towers while the remainder registered on only one or two towers. Many other towers showed traces of magnetism too small to be of value. Table I gives the tower number, leg location, crest current, degree of oscillation, and the polarity of the recorded currents. The largest stroke recorded was in mile 25 and showed 84,000 amperes on the tower hit with 17,000 amperes in the tower adjacent to the east. On the tower to the west three of the links showed the same polarity current: namely negative, while the fourth link on the south leg showed a positive current. This is one of the locations where the adjacent circuit was struck by one of the discharges in the same stroke or by another stroke. The counterpoise crosstie between the two circuits first contacts the south leg of the north circuit which could account for the reversed polarity on this leg and the resultant lower values of current than those found on the tower to the east of the one hit. The stroke current of this discharge was at least 100,000 amperes, and if the above analysis is correct was in excess of 120,000 amperes. The oscillation on the tower struck was 18 to 20 per cent while on the adjacent towers, 50 per cent oscillation was indicated, possibly due to the effect of strokes on the adjacent line or the difference in the speed of travel of the surge currents through the overhead ground wires and through the counterpoise system.

The next stroke, in mile 26, was relatively light showing only 25,000 amperes with approximately 50 per cent oscillation. The third stroke in mile four again showed oscillation of 50 per cent or greater with 35,000 amperes in the tower and only a trace on adjacent towers. The fourth stroke centered on tower 2-*N*-1 with 62,000 amperes in the tower and oscillation between 28 and 37 per cent. The tower to the east showed 8,000 amperes with high oscillation. The stroke current was at least 70,000 amperes. The last stroke of any magnitude terminated on tower 24-*N*-5 with 55,400 amperes in the tower and oscillation between 35 and 47 per cent. The adjacent tower to the west showed 15,000 amperes with high oscillation. The total stroke current was again in excess of 70,000 amperes.

From the records obtained with the magnetic links it is evident that the low-resistance counterpoise system allows appreciable oscillation, particularly on the towers adjacent to the tower struck. This may be true oscillation, or may be reversal of current flow due to the difference in speed of propagation of the waves over the different paths. The values of lightning stroke current recorded, to date are between 35,000 and 120,000 amperes, indicating that the lightning encountered in the western part of the United States is approaching the same intensity as that encountered in the East, and since observations of the counterpoise gaps indicate that values practically double these may be encountered at times, places the lightning currents well within the range of those encountered elsewhere.

To further the study of lightning current phenomena, a lightning rod assembly is being erected on eighty transmission structures and diverter towers. This assembly is pictured in figure 6. The sharp point on the top of the rod is graduated in tenths of an inch so that the amount burned off by various lightning strokes can be determined. The information gained from this should be of value in determining the size of strand necessary in overhead ground wire to prevent complete destruction by strokes terminating on the wires.

As a measure of the total current-time values of the lightning stroke, the fuse link assembly is added below the rods. Adjacent to the rod is mounted the bracket for supporting the magnetic-link-type surge-crest ammeter while the paper-film-gap type is mounted on the supporting steel member at the base. A device for counting the number of discharges in multiple strokes is in the process of development to fill the vacant space between the last fuse-link clip and the film-type crest ammeter. It is hoped that this equipment will add some further information as to the effect of burning of lightning strokes as well as some data on the multiple stroke currents.

## Conclusions

The insulation design selected for the fog section of the transmission line gives satisfactory performance, practically free from noise and perfectly free from outage if washed at occasional intervals as contemplated.

To date there have been 173 strokes to the Boulder Dam transmission line, none of which is known to have flashed an insulator assembly. Approximately 70 of these hits occurred since the line has been energized.

The counterpoise gaps used to break the electrolytic circuit between the tower steel and the counterpoise give very desirable indications of the towers hit by lightning and serve to give an approximate indication of the magnitude of the stroke.

Magnetic-link-type surge-crest-ammeter records have showed during one lightning season, currents as high as 84,000 amperes down a single tower and in excess of 120,000 amperes in stroke current.

The adequacy of the lightning-protection scheme has been largely substantiated by the past year's experience, and future performance will determine the exact factor of safety that was built into the lines.

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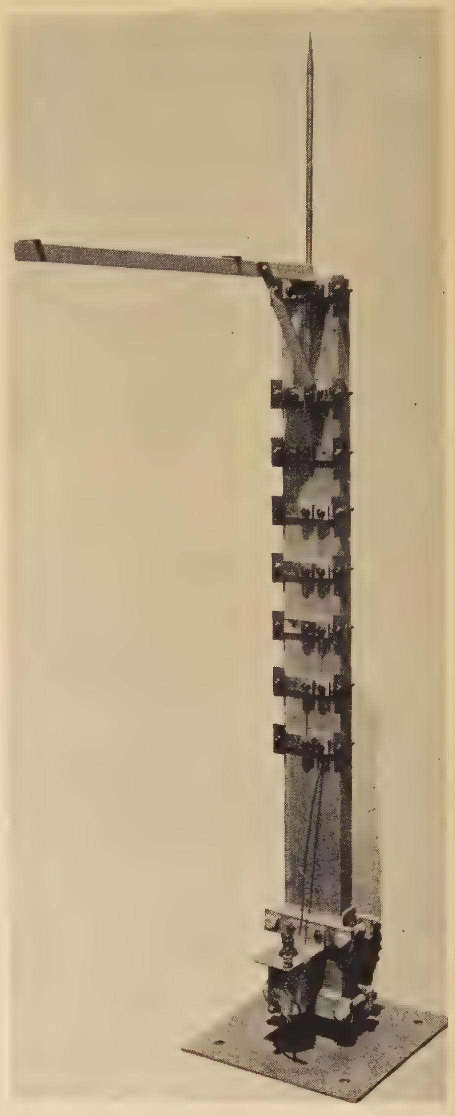

**Figure 6. Lightning rods for tower tops, points to indicate degree of stroke burning, fuse links to indicate total current times time, with magnetic link crest ammeter at top and paper film crest ammeter at base**

# Symposium on Operation of the Boulder Dam Transmission Line—Carrier-Current Equipment

By J. D. LAUGHLIN
ASSOCIATE AIEE

CARRIER-CURRENT equipment is being employed for three distinct services on the Boulder Dam transmission line: first, for pilot channels for automatic protective line relays; second, for a transmission channel for supervisory control equipment which provides control from Boulder power plant of the two switching stations between Boulder and Los Angeles; and third, for telephone communication between Los Angeles, Boulder, and the two intermediate stations, and to transmit orders to line patrolmen who may be working at any point along the line. These three functions may be performed simultaneously without interference with each other, and are not affected by power conditions or normal switching conditions on the line.

This paper deals with the supervisory control equipment, the telephone equipment, and certain equipment common to all services. The relay installation is discussed in a companion paper in this symposium entitled "Transmission Line Relay Protection."

Important savings in operating time and in investment have been achieved by the use of carrier-current equipment for these functions. As Boulder power plant is the major source of power for the City of Los Angeles, and in order to increase the stable power capability of the line, it is necessary that faults be cleared with a minimum disturbance to the system, and that outages be reduced to a minimum. The use of carrier-current pilot relays provides the high-speed relay protection for individual line sections essential to maintain stability on the system during fault conditions. The carrier-current supervisory control provides a fast means of performing switching operations on the line and reduces dispatching time by providing continuous indication at both the system load dispatcher's office and Boulder power plant of the position of all switching equipment on the line. Due to the high mechanical reliability of the line and its lightning protection, the carrier-current telephone provides a communication channel more reliable and safer than could be obtained over a telephone line built through the country traversed, and at a fraction of the cost. It also provides a quick means of issuing orders to line patrolmen and thus reduces the time required to locate and repair any faults that may occur on the line.

The term "carrier current" is used here to denote currents of high frequencies that are transmitted over the metallic circuits of the power lines to perform special functions. Since the frequencies used are of the order of those used in space transmission most of the equipment used is radio-type equipment which is directly connected to the transmission line through coupling capacitors.

The carrier-current channels all operate over the 287,000-volt conductors between Boulder switch yard and Century receiving station at Los Angeles. The relay channels stop at these stations. However, from Boulder switch yard to the power plant the supervisory and telephone carrier channels operate through coaxial cables. From Century station to the load dispatcher's office in Los Angeles the supervisory and telephone operate over direct-wire channels.

The equipment required for carrier-current transmission consists first, of radio-type transmitters that generate the carrier frequencies and are controlled by signaling devices which may be relays, if it is desired to transmit codes, or microphones for voice transmission; second, tuned coupling devices for connecting the carrier sets to the transmission line; third, the transmission line and, fourth, radio-type receivers that rectify or demodulate the messages received. There are also auxiliary devices for blocking the carrier out of stations and bypassing station equipment.

All carrier-current equipment installed on the Boulder transmission line is designed to operate at any frequency in the wave band from 50 kilocycles to 150 kilocycles, and is designed to operate at 10 kilocycles separation between adjacent-channels without interference. This band permits the use of eleven channels at this spacing, of which there are now eight channels in use and more channels will be added later. The supervisory control equipment is operating at 60 kilocycles, the telephone at 90 kilocycles, and the relay circuits at 110, 117, 130, 135, 140, and 150 kilocycles.

Each relay carrier channel operates over one line section only, and since transmission is required only when there is no fault condition on the line, one conductor and ground provide a satisfactory circuit. For the supervisory and telephone services it is necessary to maintain carrier transmission during abnormal conditions. For each of these services, one conductor in each line of a different phase is used with the midpoint between the line tuning units grounded so that if one conductor of these circuits becomes open, transmission is maintained through the other conductor and ground. Phase *A* of each line section is used exclusively for the pilot relaying carrier channels. Phase *B* of each section of the north line and phase *C* of the south line are used exclusively for the supervisory control carrier channel. Phase *C* of the north line and phase *B* of the south line are used exclusively for the telephone carrier channel.

The line coupling devices used to connect the carrier sets to the transmission line consist of a capacitor connected to the line conductor and to ground through a variable tuning inductance and one wind-

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## Discussion

For discussion see page 156.

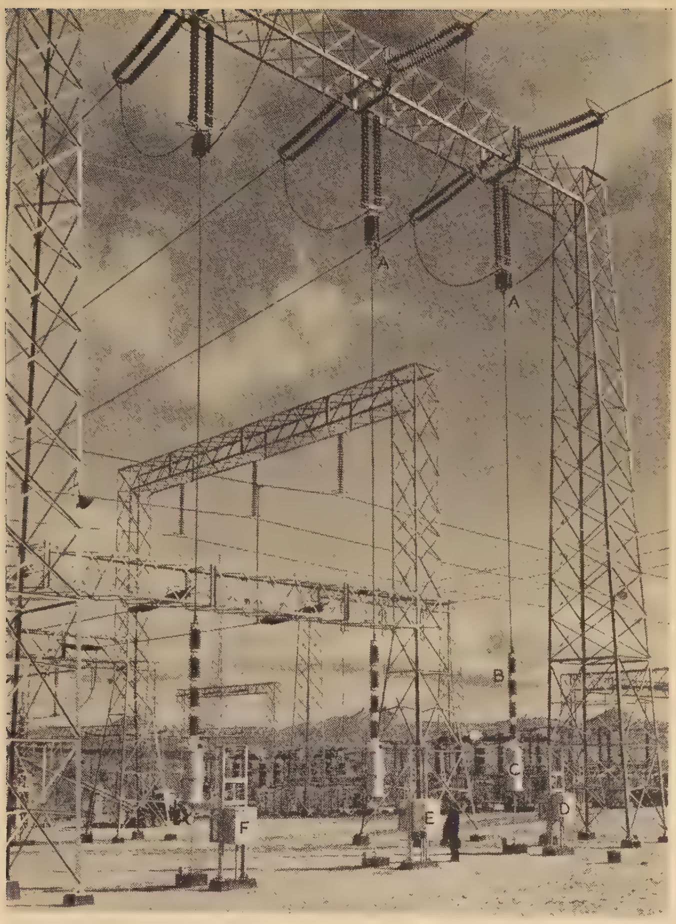

**Figure 1. Line coupling equipment**

*A*—Wave traps
*B*—Coupling capacitor
*C*—Potential device
*D*—Supervisory line tuning unit
*E*—Relay carrier set
*F*—Telephone line tuning unit

ing of a repeating coil. There is a coupling device connected to each conductor entering the station, and a wave trap between each coupling device and the station (figures 1 and 2).

Each coupling capacitor consists of four porcelain-housed units in series, each consisting of 40 series units, using aluminum foil plates, insulated with kraft paper, giving a capacity of 0.00075 microfarad for the complete unit. The porcelain housings are evacuated, then filled with insulating oil to within several inches of the top of the metal cap. This top space is filled with an inert gas and hermetically sealed to provide a cushion to prevent excessive pressures due to expansion in hot weather.

At the lower end of the capacitor the circuit divides, one branch being a carrier-frequency circuit and the other a power-frequency circuit. A 0.03-microfarad condenser, in the carrier-frequency circuit, blocks the passage of power-frequency currents and a 0.24-henry choke coil, in the power-frequency circuit, blocks carrier-frequency currents. From the small condenser the carrier-frequency circuit goes to the line tuning units. The tuning units for the three services are slightly different in construction, but each consists of a variable inductance by means of which the circuit from line conductor through capacitor, tuning unit, and repeating coil can be tuned to resonate at any frequency between 50 kilocycles and 150 kilocycles. In order to bypass station equipment, the tuning units at the two ends of the station for the supervisory carrier are connected together with underground coaxial cables; the telephone tuning units are similarly connected. The carrier sets are connected in the circuit between the tuning units (figure 3).

The 60-cycle circuit from the radio-frequency choke is completed to ground through the primary of a potential device having a capacity of 150 watts at 115 volts to provide energy for relay potential coils. The secondary of this device is connected to an adjusting unit by means of which phase angle and ratio adjustments are made.

The wave traps in the line between the coupling capacitors and the station are adjustable to block any single frequency within the carrier band from entering the station equipment and becoming dissipated in losses in the equipment or in closed shorting and grounding switches. For the supervisory and telephone services they also force the carrier currents to go through station bypasses, and thus provide approximately the same circuit characteristics regardless of the position of station equipment. The traps used for the three services are essentially the same; they consist of a large coil shunted by adjustable groups of small fixed condensers of various sizes in series with a variometer. The inductance coil in the traps used in the relay circuits consists of 31 turns of 750,000-circular-mil cable wound on a 15-inch-diameter porcelain shell. Those used in the traps for supervisory and telephone circuits consist of 36 turns of $^7/_8$-inch diameter solid hard drawn copper rod wound in two layers of 15-inch and 19-inch diameters supported on a bakelite frame. A protective gap and lightning arrester are connected across the trap to protect the capacitors in case of high voltages due to surges on the line.

All the carrier transmitters and receivers used on the Boulder transmission line operate from 115-volt single-phase 60-cycle power supplies. To insure the best reliability for their power supply, there are, in each station, two d-c motor-driven alternators obtaining power from the station control batteries and connected through automatic transfer equipment to a carrier equipment bus. Either alternator can be connected to the bus but not both at the same time. In case the operating machine fails and the bus potential drops, the second motor is automatically started and its alternator is connected to the bus. At the same time, the motor switch of the other set is opened. In case neither set starts, the bus is connected to the station lighting supply as an emergency standby. The station lighting supply is not used normally because its regulation is not considered good enough for this service. Automatic voltage regulators on the alternators hold the carrier equipment bus voltage to within one volt. The frequency varies slightly but this is not objectionable as all of the carrier equipment operates satisfactorily at any frequency between 50 and 60 cycles per second.

## Carrier-Current Supervisory Control

### CONTROL SCHEME

The carrier-current supervisory control equipment used on the Boulder transmission line provides a centralized control at Boulder power plant of the 287,000-volt switching equipment on the line, and also operates a system diagram board in the system load dispatcher's office at Los Angeles.

The operator at Boulder can perform the following operations at both Silver

Lake and Victorville switching stations: Open and close four oil circuit breakers, open and close eight disconnect switches, open and close four ground switches. There is continuous visual indication by means of colored lamps on the control board at Boulder of the positions of all this equipment and potential indications for each line section. There are also indications for the following equipment connected to the Boulder line and located in Los Angeles over which the Boulder operator has no control: four oil circuit breakers, four disconnect switches, four ground switches, and potential on two busses. On the same benchboard with the supervisory control equipment is a panel for the control of the equipment in the Boulder switch yard. This equipment is controlled by direct wire using the same type of control switches and indicating lamps that are used on the supervisory panels. From this panel are controlled four oil circuit breakers, eight disconnect switches, and four ground switches.

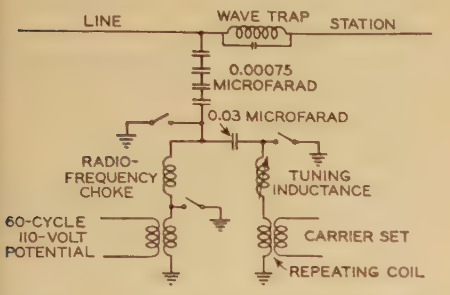

**Figure 2. Carrier-current-coupling-equipment wiring**

On the system diagram in the Los Angeles load dispatcher's office continuous lamp indication is provided by the supervisory equipment of the positions of all oil circuit breakers, disconnect switches, ground switches, and potential on lines and busses at Boulder switch yard, Silver Lake switching station, Victorville switching station, and the equipment at Century receiving station, Los Angeles, that is connected to the Boulder lines.

The Boulder operators are responsible for keeping the lines energized to Los Angeles. In case of trouble on the line, whereby Boulder becomes separated from Los Angeles, the bus breakers at Los Angeles are opened either automatically or by the local operator, depending on the nature of the trouble. The Boulder operator then energizes the line and it is synchronized with the system by the operator at Los Angeles. The control of all line circuit breakers at the two switching stations, in such a case, is by carrier-current equipment. Normally all switching in such a case would be done without telephone communication except orders for speed adjustment for synchronizing, and this order is over carrier-current equipment.

The specifications for the carrier-current supervisory control equipment require that the carrier-current equipment shall transmit and receive signals so as successfully to operate the supervisory control equipment: (*a*) under normal transmission line conditions, (*b*) without regard to the position or operation of any air-break switch, grounding switch, or circuit breaker at any of the stations, (*c*) with any one section of the transmission line solidly grounded at any point between stations, (*d*) with one phase wire to which coupling is made broken in any one section and either or both ends of the phase wire either grounded or ungrounded at the point of failure.

These requirements cover any operating conditions that are expected to occur on the line.

### Supervisory Carrier Equipment

The carrier-current equipment for supervisory control operates at a single unmodulated frequency of 60 kilocycles, transmitting codes similar to radiotelegraph signals. The carrier equipment at the four stations are duplicates, using all industrial-type tubes. The transmitter circuit consists of a Colpitts oscillator, followed by one stage of class-*A* amplification and one stage of push-pull class-*B* amplification. Keying is done in the oscillator grid circuit. The keying relay is of the type used in high-speed radio telegraphy and operates from the 48-volt supervisory-control battery and is controlled by the supervisory relays. By selection of taps on the transmitter power transformer and by the use of either two or four tubes in the output amplifier, the sets are adjustable to operate at outputs ranging from 50 to 400 watts.

The best signal levels at all stations have been obtained with the transmitters at Boulder and Los Angeles operating at 400 watts output, and those at Silver Lake and Victorville at 200 watts output.

The receivers employ a special self-regulating heterodyne circuit. The receiver output operates a receiver relay which in turn controls the supervisory relays.

Test telephone sets are provided which can be plugged into the transmitter and receiver circuits for temporary communication.

The Boulder control board is a steel benchboard with four panels, one for Boulder switch yard, one for Silver Lake switching station, one for Victorville switching station, and one for Century receiving station at Los Angeles. On the benchboard there is provided, in a mimic bus system, an individual control key and indicating-lamp escutcheon for each piece of apparatus remotely controlled or supervised. Associated with these lamps and keys, and controlled by the operations of the keys, are groups of small multicontact relays mounted on relay panels. A similar installation of multicontact relays is made at each remote station. At the remote station, however, the relays are controlled by the operation of those at Boulder by carrier impulses transmitted over the line and are connected through their contacts to interposing relays which, in turn, cause the devices in the remote station to function in response to the operations initiated by the Boulder operator.

Separate independent codes are used for the selection of each device. For common functions such as close, trip, supervisions, Los Angeles check and release, a group of codes common to all points is used. Guard circuits are incorporated in the equipment that prevent the completion of a selection sequence if the selection code is not received correctly.

When an individual selection key is pulled on the benchboard, the Boulder transmitting relays set up and place on the line the predetermined selection code for that point. This code is transmitted from Boulder to all other stations. The function of this code is to select for operation the switch corresponding to the escutcheon on which the operator pulls out the selection key, and to select the corresponding point on the Los Angeles dispatcher's board. When the point selection code is completed, check codes are transmitted from the selected station and from Los Angeles, which cause the individual point selection lamp to be lighted on the escutcheon on the Boulder board corresponding to the equipment selected.

To close the breaker the operator now sets the individual twist type control key in the close position and then depresses the master control key. This causes the Boulder transmitting relay to send out a close code which is registered by the selected station's receiving relays and they, in turn, cause the "close" interposing relay to be energized, thus causing the power circuits to close the breaker. The closing of the breaker changes the position of its auxiliary switch, which, in turn, changes the position of the indication relay. This

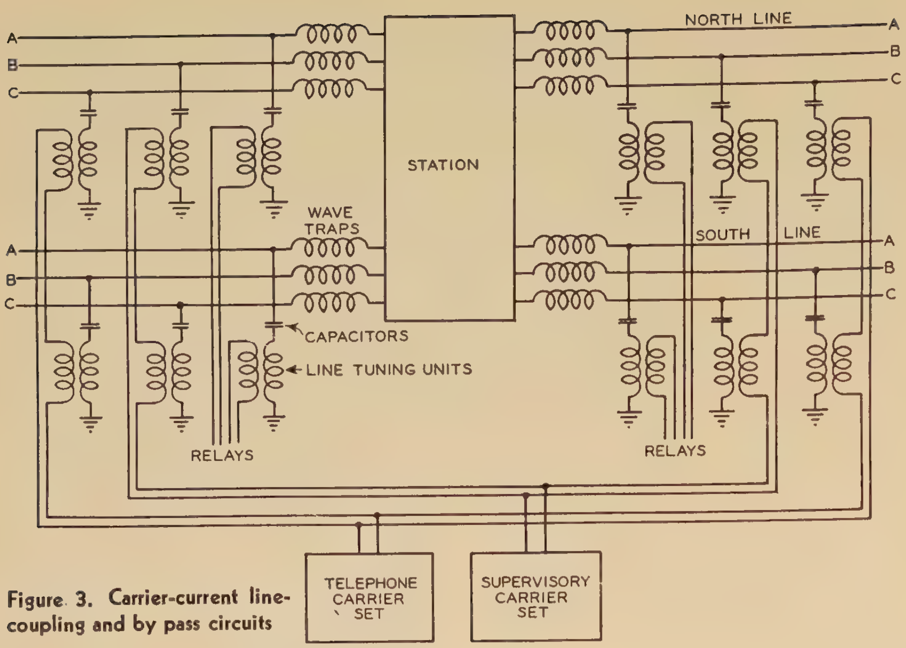

**Figure 3.** Carrier-current line-coupling and by pass circuits

relay operates to send a code which changes the position of the lamp relays for the selected breaker, thus causing the indicating lamps to change from green to red at Boulder and Los Angeles and completing the entire operation. The elapsed time from pressing the master control key until the lamps change is two seconds. Pressing the selection key resets the equipment to normal.

The operation of tripping a breaker is the same except that a trip code is transmitted to energize the "trip" interposing relay.

In case of an operation of any switching equipment by other means than by supervisory control a similar sequence occurs except that the selection code is transmitted by the equipment in the station where the operation occurred. This code is received at Boulder and Los Angeles and causes the indicating lamps to change.

Sequence of point selections is so arranged that line indications are on the first points, oil circuit breakers next, then disconnect switches and ground switches. If a line section relays due to a fault, five indications are transmitted, dead line and the opening of four oil circuit breakers, all in less than 25 seconds. If an automatic operation occurs during the sending of a code, the signal to indicate that operation is automatically withheld until the first signal is completed, and is then immediately transmitted. If a code originating in an outlying station is not correctly received at Boulder due to possible interference with the carrier or other external causes, the code is repeated until it is correctly checked or is automatically stopped after several attempts.

Interlock circuits are incorporated in the equipment that prevent the closing of a ground switch at either end of a line section if a disconnect switch is closed at either end of the section and also prevent closing a disconnect switch if a ground switch is closed at either end of the section. Circuits also prevent the operation of a disconnect switch unless its associated oil circuit breaker is open.

The equipment is so designed that trouble in any one station will not interfere with the operation of the balance of the system. Circuits are provided to sound alarms in case of a failure of the supervisory equipment. Telegraph sounders are located at the Boulder office and Los Angeles, connected in the line circuit so the operators may readily know when the supervisory is in motion.

In addition to the supervisory control all stations are provided with conventional-type remote-control switchboards and all switching equipment can also be operated manually. In case any equipment is operated from the local control boards or manually the operations are recorded by lamp changes on the supervisory boards at Boulder and Los Angeles.

### Operating Experience

After the carrier-current supervisory-control equipment was put into service it was found that extraneous signals occurred on the line with sufficient 60-kilocycle components to operate the receiver relays. These signals were generated by lightning and other discharges during rain storms, arcs that occurred when disconnecting switches were opened or closed, and transients that occurred when line sections were energized or de-energized. Any of these signals occurring during the transmission of a supervisory code would interfere with the supervisory relays registering the code properly and cause the equipment to lock out or fail to complete the operation intended. The intensity of the signals caused by rain and lightning is relatively low and could be tuned out by desensitizing the receivers; however, the signals generated by disconnect arcs and switching transients are of higher levels than the code signals during some of the abnormal line conditions under which it is required that the equipment operate. These interference signals contain other frequencies in the carrier band in addition to the 60-kilocycle component. A circuit was designed and added to the receivers that will detect these multiple-frequency signals and increase the bias on the 60-kilocycle detector tube in proportion to their intensity. This circuit reduces the rectified current due to interference signals in some cases from approximately 12 milliamperes to 0.5 milliampere which is an unobjectionable value and permits weak 60-kilocycle code signals of the order of 6 milliamperes to be rectified with no decrease in value. This circuit has eliminated one of the major troubles that has been encountered in operating this equipment.

With all sections of the line energized for normal operation the carrier transmission loss is 32 decibels. This loss is increased as sections are de-energized and grounded for maintenance work. At present there are some unusual line switching combinations that increase the carrier losses to an extent that failure of the supervisory equipment occurs but it is expected that these failures will be eliminated in the near future by increasing the transmission efficiency during abnormal line conditions.

## Carrier-Current Telephone

### Communication System

The carrier-current telephone equipment provides complete intercommunication between Boulder, Silver Lake, Victorville, and Los Angeles, on a single carrier frequency of 90 kilocycles. This telephone channel is used for load dispatching, general communication, and for giving orders and instructions to transmission-line patrolmen cruising in automobiles in the vicinity of the transmission line.

The specification requirements for abnormal operating conditions are similar to those for the supervisory control. During normal operating conditions on the line this equipment provides excellent telephone service from the standpoint of speech quality, and provides good quality and continuity of service during abnormal line conditions. On the occasion when a double-circuit tower fell during a flood, five of the six conductors were broken, the conductor that remained in the air was one to which the telephone channel was connected and communication was maintained through this condition until a repair crew grounded this conductor.

This equipment uses the single-side-band carrier-suppressed principle of transmission. All the transmitted energy is concentrated into one side band which contains all the frequencies that are essential to reproduce the original speech. This equipment operates on a single-frequency channel for transmission in both directions and employs voice-actuated vacuum-tube circuits to start the transmitter and block the receiver when transmitting and reverses this operation when receiving. Normally the transmitter is held inoperative by the introduction of a high negative bias on the grids of the modulator tubes and the receiver is normally set to receive signals. Speech currents introduced into the transmitting circuits are at the same instant introduced into the duplex control circuit. The speech currents in the duplex control circuit act to unblock the modulator and to block the demodulator. This allows the transmitter to become operative after the receiver is blocked, thus permitting the modulated speech to be introduced into the power amplifier and thence through the coupling equipment to the transmission line. The design of the duplex circuit is such that the unblocking of the transmitter and blocking of the receiver is almost instantaneous when talking is started. A certain amount of delay is provided in the release of this circuit in order to prevent the transmitter from blocking and the receiver from unblocking between syllables or between words at average talking speeds. To prevent received speech from actuating the transmitter at the receiving terminal, the received speech operates on the duplex control circuits and prevents it from actuating the transmitter.

This equipment operates similar to a party line with selective ringing. Any station can hear all conversations on the line. Selective ringing is provided between all terminals. This is accomplished by employing an audio-frequency tone of 1,615 cycles which is controlled by conventional telephone dials. The code of audio-frequency pulses is transmitted from the calling terminal and received at all other terminals. These pulses actuate sequence switches of a type used in automatic telephone exchanges. At the receiving terminal corresponding to the code dialed, relays are operated which cause a signal bell to ring. Ring-back facility is provided so that when a bell at a station is being called a 1,615-cycle tone is transmitted back to the calling station.

A two-wire extension line is run from Century station to the main office *PBX* board in Los Angeles where telephones in the main office can be connected to the carrier system. The system load dispatcher has the right of way over all other terminals and can break into any conversation and ask for the use of the line.

Power required for the operation of this equipment is supplied from a 30-volt d-c source and from a 115-volt 60-cycle source. At one location a storage battery is used to supply the direct current and at all others copper-oxide-type rectifiers supplied from the 115-volt service. As the equipment must be ready for instant service it is always kept energized. Each equipment transmitter has a rated output of 125 watts.

Patrol cars along the transmission line are equipped with radio receivers tuned to the telephone frequency. When it is desired to issue instructions to patrolmen, the dispatcher impresses a special tone on the carrier which is received by all cars. When the patrolmen hear this tone they turn up their receivers and get whatever message is on the line. These car receivers will pick up messages at any point along the line patrol road, and the performance has been very satisfactory.

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## Discussion

For discussion see page 156.

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# Symposium on Operation of the Boulder Dam Transmission Line—Transmission Line Relay Protection

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When the study of these lines for the application of protective relays was started the predetermination of fault currents made it necessary to calculate all of the phase-sequence constants of the lines since none of these constants for conductors of this size and spacing was available.

The elements entering into the calculation of the positive-phase-sequence characteristics were easily determined and the proper method for their consideration has been fairly well fixed by previous practice. This was not the case for the zero-phase-sequence characteristics since the equivalent depth of the ground-return circuit could not be easily determined and there was no previous experience with a continuous buried counterpoise such as was to be used with this line. In making these calculations the equivalent depth of the ground return circuit was taken as 8,800 feet and the counterpoise was considered as though it did not make contact with the earth, or in other words as though it was part of the overhead ground wire system. The depth of the ground-return circuit used which corresponded to

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1. For all numbered references, see list at end of paper.

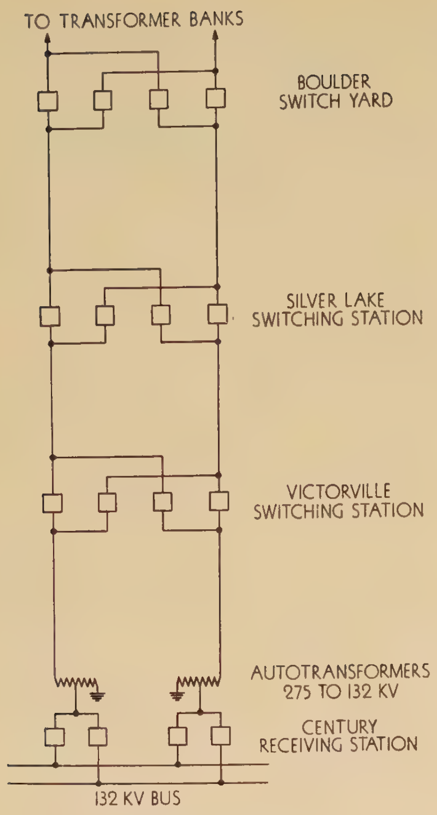
TO TRANSFORMER BANKS
BOULDER SWITCH YARD
SILVER LAKE SWITCHING STATION
VICTORVILLE SWITCHING STATION
AUTOTRANSFORMERS 275 TO 132 KV
CENTURY RECEIVING STATION
132 KV BUS

**Figure 1.** **One-line diagram of Boulder Dam transmission line**

dry earth was probably somewhat small for the territory over which this line was to be built and would consequently give values of impedance that were low; on the other hand, considering the counterpoise as not being in contact with the earth should give values of impedance which were high. Because of the manner in which these two factors entered into the calculation of the zero-phase-sequence impedance of the line it was believed that the final results would, if anything, be slightly high, and since they were to be used in determining the minimum current conditions for protective relays this was far more desirable than impedance values which might be low.

The line constants were first calculated for 50 cycles and a complete study of the short-circuit currents and voltages for all types of faults at each bussing point on the line was made. From this study it was apparent that if the shunt capacitance of the line was neglected the errors in current and potential, while quite large at some locations, were small at the locations under consideration in this study, and were entirely negligible at the locations which would be most difficult to protect.

When it was definitely decided that the system frequency would be changed from 50 cycles to 60 cycles it was a comparatively simple matter to recalculate the line characteristics, since a great deal of the work done during the 50-cycle calculation was not changed, and in view of the negligible errors introduced by neglecting shunt capacitance during the 50-cycle short-circuit study, it was decided to neglect this capacity in the 60-cycle study. The results of the 60-cycle study for three-phase and single-phase-to-ground faults have since been checked, using the distributed constants of the line and the above decision was entirely justified by these checks.

The results of the short-circuit study indicated that, under minimum fault conditions, the current available for operation of the protective relays would be less than the maximum load current the line would be required to carry, that the most difficult fault to clear would be a phase-to-ground fault on the 132-kv side of the autotransformers at Century receiving station and that with a phase-to-ground fault at this location when the parallel circuit was out of service the relays at Victorville could not be expected to function unless the delta connection of the autotransformer tertiary winding was opened.

## Trials of Equipment

Carrier-current pilot protection seemed most desirable for these lines; however, it was felt that some operating experience with this type of protection should be had before a definite decision was made. Equipment of this type was purchased and installed on two parallel 132-kv transmission lines, together with a scheme of balanced current protection.

Two different types of carrier pilot protection were used; one line was equipped with an intermittent carrier type in which carrier current is only transmitted when a blocking impulse is desired, because of external fault; the other line was equipped with a continuous carrier type in which carrier current is transmitted continuously, and only stopped at both ends when an internal fault occurs on the line. Both types performed quite satisfactorily during faults on the system, both internal and external, but the continuous carrier type had the disadvantages that it caused interference on nearby broadcast receivers, and that the tubes in this type were required to carry plate current continuously.

The broadcast interference was due to the fact that it was impractical to operate the transmitters at the two ends of the line at exactly the same frequency and therefore an audible beat frequency equal to the difference between the two transmitter frequencies was produced. This audible beat frequency was heard in nearby broadcast receivers whenever these receivers were tuned near some multiple of either of the transmitter frequencies.

While no trouble of a serious nature was encountered with either of these equipments, other than that described above, the experience gained proved very valuable in preparing specifications for the Boulder line relays and in adjusting that equipment when it was installed.

## Specifications

In addition to all of the ordinary features that would be required of any scheme of line protection the following special requirements were considered highly desirable in the Boulder line protection: (1) all faults on these lines should be cleared in not to exceed 0.15 second from the inception of the fault, until the last breaker was open, and (2) the protection should be immune to operation on an out-of-step or surging condition. The only types of protection that would possibly fulfill both of these special requirements are high-speed current balance protection and carrier-current pilot protection.

The maximum time required by the oil circuit breaker on these lines is three cycles or 0.05 second, and at the time the specifications were written it was uncertain if operating time shorter than 0.05 second could be obtained with carrier-current relays. This would mean that the settings of the carrier-current relays would have to be sufficiently sensitive to secure simultaneous operation of the relays at the two ends of a line section, or the total time would be extended beyond 0.15 second. Such low settings were undesirable and could be eliminated by the installation of high-speed current balance relays which would operate in 0.025 second or less so that even with full cascade operation of the relays and breakers at the two ends of a line section the total clearing time would not exceed 0.15 second.

The specifications were prepared on the basis of using both carrier-current pilot protection and high-speed current balance protection and the following performance requirements written in: The current balance protection shall operate simultaneously at both ends of a faulty circuit for any fault occurring within the center 70 per cent of the electrical length of the circuit but may operate sequentially for faults occurring within 15 per cent of the electrical length of the line from either end. The time required by the relays in either case shall not exceed 0.025 second. With one circuit of a section carrying 300,000 kva and the other circuit open, the circuit carrying the load shall not be tripped when the other circuit is closed at either end.

The carrier-current pilot protection as a whole shall:

1. With minimum system condition and both circuits of the section in service energize the oil circuit breaker trip circuits at both ends of a faulty circuit in not to exceed 0.05 second for all faults occurring within the center 70 per cent of the electrical length of the circuit.

2. With minimum system condition and both circuits of the section in service energize the oil circuit breaker trip circuits at the end of a faulty circuit adjacent to the fault in not to exceed 0.05 second for all faults occurring within 15 per cent of the electrical length of the line from that end, and shall energize the oil circuit breaker trip circuits at the end remote from the fault in not to exceed 0.05 second after the circuit is opened at the end adjacent to the fault. The above time requirement may be exceeded if all voltages are less than five per cent of normal and no secondary current is greater than ten amperes.

3. Not cause tripping for instability or external faults under any condition.

4. Clear ground faults occurring while the system is unstable without any purposely introduced time delay.

5. Clear phase-to-phase and three-phase faults occurring while the system is unstable with the minimum practical delay consistent with the requirement that instability shall not cause tripping.

6. Remain inoperative with a load of 300,000 kva on any one circuit and no fault on the system.

7. Not delay tripping for internal faults that occur immediately after any external fault except a three-phase external fault.

8. Be entirely self-contained and shall not depend upon the operation of any piece of apparatus not directly associated with the line protected.

Other requirements of a special nature were an automatic complete carrier transmission and reception check in both directions once every hour, and a pair of portable telephones that could be plugged into the relay carrier sets at the two ends of a circuit for temporary communication during adjustments.

## Description of Equipment

Four high-speed current balance relays are used for each end of a pair of circuits, three for phase faults and one for ground faults. Each relay has two balance beam units and each unit is equipped with four coils and circuit-closing contacts for tripping two breakers. The coils are a current operating coil, a current restraint coil, a voltage restraint coil, and a d-c holding coil. The current operating coil of one unit is connected in series with the current restraint coil of the other unit, thus forming two separate current circuits for the relay which are connected one in the same phase-current-transformer secondary circuit of each line. The units trip the two oil circuit breakers associated with the line supplying their operating current.

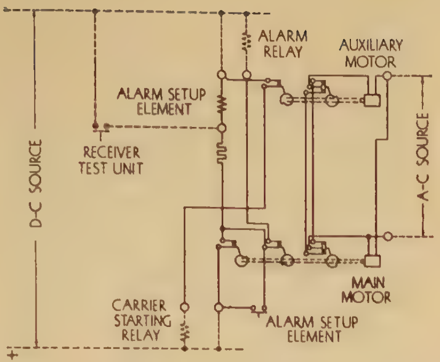

**Figure 2. Diagram of automatic carrier test relay showing internal and external connections**

The voltage restraint coils of the phase relays are supplied with phase-to-phase voltage, which leads the current used on the relay by 30 degrees at unity power factor. The voltage restraint coil on the ground relay is not ordinarily used.

A carrier-current pilot relay is used in which all of the necessary relay elements for the complete protection of a line terminal are incorporated in one case. This relay and the scheme of protection used is the same as described by Traver and Bancker,[1] except that two ground-fault detector elements are used and the functions of the ground-fault detector in the relay described are divided between these two in the same manner as they are with the phase fault detectors. In addition a normally open contact on the *A* ground-fault detector shunts the contacts of the block cut-off and block continuing units in the master oscillator grid circuit to prevent any delay in tripping ground faults occurring during instability.

An automatic carrier test relay and two auxiliary interposing relays in separate cases are used for each line circuit terminal in addition to the carrier pilot relay. The interposing relays are used one between the automatic carrier test relay and the master oscillator grid circuit, and the other between automatic test relay and the alarm circuits. A schematic circuit diagram of the automatic carrier test is shown in figure 2. The automatic carrier test relay contains a main and an auxiliary sychronous-motor-driven cam shaft, and an alarm setup relay element. The motors receive energy from the capacitor potential devices connected directly to the line and the main motor operates continuously, driving its cam shaft at one revolution per hour and operating three separate sets of contacts at 20-minute intervals. The auxiliary motor drives its cam shaft at the rate of four revolutions per minute but it is controlled by one set of contacts on the main cam shaft in such a manner that it only travels one revolution, in two steps of approximately one-half revolution each, for each revolution of the main cam shaft. A set of contacts actuated by the auxiliary cam shaft causes the carrier transmitter to operate for a period of 0.5 second and the only function of the auxiliary motor and cam shaft is to obtain this very short operation of the carrier transmitter, which could not be reliably obtained with a contact actuated directly by the slower-moving main cam shaft. Twenty minutes after the operation of the first set of contacts on the main cam shaft the second set of contacts picks up the alarm setup relay element which locks itself in, then 20 minutes later the third set of contacts on the main cam shaft completes the alarm circuit unless the alarm setup relay element has been released in the meantime by operation of the receiver test unit in the carrier pilot relay.

The main cam shafts on the automatic test relays at the two ends of a line circuit are set 180 degrees or 30 minutes apart and always remain in the same relative positions since they are always energized and de-energized together, thus carrier is transmitted from the remote end of the circuit midway between the operation of the second and third set of local contacts and no alarm will be given unless the carrier signal is not received locally. The receiver test unit has a pickup setting that is 25 per cent greater than the receiver blocking unit so that the gradual reduction of the received carrier signal which might be caused by the falling off in emission of a tube will give an alarm before actual failure has taken place.

The portable telephones can be plugged in either at the relays or at the carrier sets and a transfer circuit is arranged so that the portable telephones can be set up at the carrier sets on one line but the carrier sets on the other line used for communication. The circuits are so arranged that the operation of the carrier test, either manual or automatic, or the use of the portable telephones will not in any way interfere with the correct operation of the relays should a fault occur while any of these were in operation.

The carrier sets are contained in double-walled thermal-insulated metal cabinets which are mounted on the switch rack near the coupling capacitors. These sets consist of a line tuning and safety panel, a transmitter-receiver shelf, and a power rectifier shelf. The transmitter is a single-tube master oscillator with a push-pull type amplifier and has an output of approximately 25 watts. The receiver uses a single three-element tube of the same type used in the oscillator and amplifier. All tubes are biased to cut off when no signal is being transmitted or received. Grid bias voltage is obtained directly from the station control battery and the filament and plate supply is obtained from motor generators which are driven from the control battery.

Copper-oxide rectifiers are used as valves in the tripping circuits of all oil circuit breakers, as shown in figure 3, to prevent false tripping in the event these trip circuits should be tied together through the contacts of some of the protective relays which are blocked either automatically or manually. This is believed to be the first time copper-oxide rectifiers were ever used for this purpose, and saves the time of auxiliary tripping relays or the complication of a pallet switch interlock scheme which might be used for the same purpose.

Potential for the relays is obtained from three capacitor potential devices connected directly to each line end at all points except Century receiving station where potential for all the relays except the automatic test relay is obtained from either of the two 132-kv bus potential transformer banks through a manually operated transfer relay. The auto-test relays at this station are supplied from a single capacitor potential device connected directly to each line.

Current is supplied from cascade-type current transformers in the impulse-type oil circuit breakers at all locations except Boulder, where the conventional bushing-type current transformers on the oil circuit breaker bushings are used.

The relay carrier sets are coupled between *A* phase and ground on all circuits using the same coupling capacitors as are used for the potential devices. A wave trap which can be tuned to any frequency from 50 to 150 kilocycles is connected into the line at each end between the coupling capacitor and the station.

A single-pole oil circuit breaker is installed in the delta connection of the tertiary windings on each of the autotransformer banks at Century receiving station. This breaker is for the sole purpose of opening this delta connection in the event of a phase-to-ground fault between the bank and the 132-kv breakers, when the parallel line circuit is out of service, so that sufficient residual current will flow at Victorville to operate the relays at that point. This single-pole breaker is tripped by an inverse-time excess-current relay operated by circulating current in the delta connection. A minimum time setting of approximately 0.3 second will prevent this relay from operating under conditions when it is not necessary and will allow it to operate when necessary in a sufficiently short time to prevent serious damage by the fault. System stability will not be affected by the time of operation of this relay because, under the condition when it is necessary for this relay to operate, the system will have been separated from Boulder power plant and the fault by the carrier-current protection at Century receiving station.

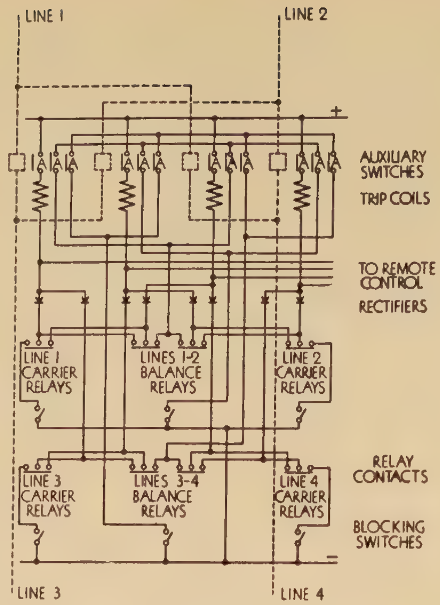

**Figure 3. Schematic diagram of tripping circuits showing use of copper-oxide rectifiers**

High-voltage leading-current protection is installed on these lines at Century receiving station that will automatically open both lines in the event the lines should be opened at Silver Lake switching station or at Boulder and the leading kilovolt-amperes of the lines should cause high voltage on the receiving-station bus.

## Tests

The high-speed current balance relays and the carrier-current pilot relays were all tested at the factory, using two test tables as described by Traver and Bancker[1] to simulate the actual line conditions under which these relays would be required to operate in service. Two of the carrier sets which were to be used with these relays on the line were used in the tests and coupled together through an artificial transmission line. All types of faults, both internal and external as well as out-of-step and surging conditions in which the electrical center of the system fell within and outside of the protected line were tried. Oscillograms were taken of each test and the operations of the relays were entirely satisfactory. As a matter of fact the tripping time of the carrier-current relays was considerably shorter than was required by the specifications due to the development of the so-called one-cycle scheme of carrier-current protection between the time of writing the specifications and the start of manufacture of the equipment.

## Installation

Upon receipt of the equipment at Los Angeles each element of the relays was checked to make sure that the adjustments had not been disturbed during transportation. Carrier frequencies between 110 and 150 kilocycles were assigned to the various circuits, an attempt being made to keep as wide a separation as possible between the frequencies assigned to parallel circuits and to circuits terminating in the same stations. The wave traps for each section were tuned before installation and marked for the station, line, and phase in which they were to be installed.

The carrier sets were installed and ready to operate before work was completed on the lines themselves and to save time it was decided to adjust these sets without interfering in any way with the work on the line and to check these adjustments when the line was completed, making any readjustments necessary at that time. To make these adjustments a ground was placed on the line side of the coupling capacitors and a noninductive resistor connected in series with the carrier lead-in wire to limit the output of the transmitters. A resonant-type wave meter was used to set the oscillators to their assigned frequencies and then, using the transmitters as a source, the line coupling and the receiver primary and secondary were tuned to resonance. The coupling of the oscillator transformer and the receiver transformer were adjusted at the same time. After all sets had been adjusted by this method and the lines had been completed a check was made between the two ends of each line circuit, which revealed that operation would have been entirely satisfactory on all circuits without any further adjustments and the only improvement that could be made was a readjustment of the receiver primary tuning, which increased the received signal by a very slight amount. The usual wiring check and over-all tripping tests were made before placing the relays in service.

## Operating Experience

The amount of trouble experienced with the protective equipment on these lines is considered remarkably small in view of the size and extent of this project. What trouble has been experienced can be classified under four different headings, (1) vacuum tubes, (2) rectifiers, (3) wave traps, and (4) switching transients.

### (1) VACUUM TUBES

This trouble is hardly worthy of mention in that out of a total of 60 vacuum tubes used in the relay carrier sets, one rectifier tube has failed in a year of continuous operation.

### (2) RECTIFIERS

Potential restraint for the phase-fault detector elements of the carrier-current relays is secured from the line potential devices through full-wave copper-oxide rectifiers. This is done to secure pickup characteristics of these elements which are practically independent of phase angle and to reduce the potential burden of the relay. Shortly after the line was placed in service these rectifiers failed in one of the relays. The failure occurred at a desert switching station which was the highest voltage point of the line under the operating condition at that time and where the ambient temperature was high, although not unusually so for that location. Upon investigation it was found that these rectifiers at all locations were operating at temperatures higher than were desirable and additional ventilation was provided by portable electric fans as a temporary remedy and no further trouble was experienced. New rectifiers of the same type but with 28 per cent more plates were installed and a resistor, which was the principal source of heat in the relay case where the rectifiers are mounted, was replaced by an external resistor. Since this change was made the equipment has been in operation through a summer season without undue heating of the rectifiers and no further trouble has been experienced.

### (3) WAVE TRAPS

The line wave traps used with the carrier relays were tuned to resonance at the assigned frequency by a group of fixed condensers and a variable condenser which was used to obtain capacities in between those that could be obtained by different grouping of the fixed condensers. Shortly after the beginning of the lightning season along the line failure of carrier was indicated on one circuit by the operation of the automatic carrier test alarm. Upon investigation the trouble was located in one of the line wave traps. Flashover had occurred between the plates of the variable condenser and had eventually built up a globule of the plate material which shorted the condenser and detuned the trap. This same trouble occurred on several other traps at various times and in each case was revealed by the automatic test equipment within a few minutes after it had occurred. As a temporary expedient the short was removed with a file in each case and the trap returned to service. As a permanent cure the variable condensers were replaced by a small variable inductance in series with a group of fixed condensers and this has apparently completely eliminated the trouble.

### (4) SWITCHING TRANSIENTS

When switching operations are carried out on these lines quite large transient currents flow. The only time these transient currents have caused trouble with the relays is when a line circuit is picked up at normal voltage or when an unloaded circuit is paralleled with a circuit that is carrying load. All trouble experienced has been with the ground relays. Numerous oscillograms have been taken which reveal that these transients have frequencies from 120 cycles to upward of 700 cycles per second with or without a d-c component. The d-c component appears when an unloaded circuit is paralleled with a loaded circuit and also when a circuit containing the autotransformers is energized. The high-frequency transient appears in practically all cases but is apparently suppressed when the d-c component is present.

The minimum pickup of the balance current ground relays was increased from one ampere to two amperes at all locations and in addition at Century receiving station these relays were further desensitized for a short period of time after paralleling the two circuits by energizing the potential restraint coils from the control battery when one or both circuits are open, and removing this potential restraint automatically approximately two seconds after the lines are paralleled. This method has apparently cured the trouble in so far as the current balance relays are concerned, and since it introduces no objectionable restrictions to their operation on faults is considered as permanent.

The minimum pickup of the ground-fault detector elements in the carrier-current pilot protection was increased from 1 ampere to 3 amperes for the starting, or *A* detectors, and from $1^1/_4$ amperes to 4 amperes for the tripping, or *B* detectors. No trouble has been experienced since these settings were increased and they are still sufficiently low to clear all ground faults; however, this method is objectionable because under some minimum conditions the time of clearing will be extended longer than is desirable.

A transient filter has been developed for use with the ground tripping fault detector that will effectively block all frequencies of 120 cycles and above, as well as d-c transients, from the fault-detector coil without materially affecting the pickup characteristic of the detector on frequencies from 35 cycles to 85 cycles. These filters are being manufactured at the present time and when installed will permit resetting the ground-fault detectors to their original pickup values. No filter will be used with the starting-fault detector since there is no objection to its operation by the transient currents.

During the extremely severe flood conditions of March 2, 1938, one of the twin-circuit towers on the Victorville-Century section of the lines was washed out, causing a fault first on the north line and six minutes later on the south line. The north line was cleared by the balanced current protection at both Victorville and Century in a total time of $3^1/_2$ cycles. The south line was cleared by the carrier-current protection in $5^1/_2$ cycles at Century and $10^1/_2$ cycles at Victorville.

The fault on each line was single-phase-to-ground and the longer time required at Victorville was due to the ground current being only slightly above the pickup settings of the ground-fault detector elements. If the transient filters described above had been installed at this time and the pickup settings of the ground-fault detectors restored to their original values, the time required for clearing the south line at Victorville would have been considerably reduced and would probably have been of the same order as the time at Century.

These faults, as well as numerous other faults which have occurred on the system at various times, have demonstrated the ability of the carrier-current protection properly to block tripping on through fault conditions.

During the oscillographic investigations of the switching transients simultaneous records at the two ends of a 90-mile circuit were obtained in the following manner: Load was being carried over one circuit between Boulder and Victorville and records of the terminal conditions of the loaded circuit at both Boulder and Silver Lake and the Silver Lake terminal conditions of the dead Silver Lake-Victorville circuit were desired at the instant of energizing the Silver Lake-Victorville circuit at Silver Lake. A six-element oscillograph was used at Boulder, and two oscillographs, a nine-element and a three-element, with their drums mechanically tied together, were used at Silver Lake, giving six elements for each line terminal being considered. A contact on the drum shafts at each station was used to sound a buzzer once for each revolution of the drums The control circuit for the oscillograph shutter and oil circuit breaker closing at Silver Lake were arranged so that by closing a single contact both functions would occur in the proper order to obtain a record of the change in line terminal conditions when the breaker contacts closed. The control circuit for the oscillograph shutter at Boulder was arranged in the same way so that all that was necessary was to synchronize the film drums at the two stations and close the initiating contacts in both stations at the same time. The synchronization of the film drums was accomplished by placing the buzzer at Boulder near the microphone of the carrier telephone; the operator at Silver Lake was then able to hear both buzzers and adjusted the speed of the Silver Lake film drum until both buzzers sounded at the same time.

The operation of the initiating contacts at the same time was accomplished by taking the carrier-current supervisory control equipment out of service and using the receiver relay at both Boulder and Silver Lake to close the initiating circuits. When all was in readiness the operator at Silver Lake synchronized the film drums and then pressed a button, which started the local supervisory-control carrier transmitter.

The carrier signal being received at both stations simultaneously, closed both initiating contacts at the same time. The drum speeds used gave a total record of approximately 30 cycles and not a single shot was missed because of this method.

## References

1. A Faster Carrier Pilot Relay System, O. C. Traver and E. H. Bancker. AIEE Transactions, volume 55, June 1936, pages 688–96.

2. A Single Element Polyphase Directional Relay, A. J. McConnell. AIEE Transactions, volume 56, January 1937, pages 77–80 and 113.

# Discussion

**Abe Tilles** (University of California, Berkeley): I am certain that I speak for all present in expressing thanks to the Department of Water and Power for their broadmindedness in making public these interesting details regarding the few items of trouble that have occurred.

A number of questions come to mind regarding this outstanding transmission project. I am not sure to which member of this Department of Water and Power team of experts each of these questions falls, but I believe they will be able to sort them out without difficulty.

It was mentioned that the sending-end voltage of the line is being altered as the load varies. To what degree of refinement has it been found desirable to do this? Is the voltage setting changed manually by the operator in accordance with the load schedule, or is the voltage regulator initially adjusted to give continuous compounding of the generator voltage? How long does it take to put a generator on the line from a standstill? To what extent is automatic synchronizing equipment in use at present? What is the procedure in energizing the line?

It was mentioned that control and relaying equipment for the contemplated third line will fit along side of, and be similar to, the existing equipment. Is this the case at the switching stations as well as at Boulder? How far physically will the third line be from the others? Will it be generally similar and divided into sections? With three lines in parallel complications arise in a scheme of high-speed parallel protection. How, in a general way, will the three lines be protected? If the receiving third of the third line is not directly in parallel, can the carrier-controlled relaying on that section be sped up?

It was mentioned that tube failures in the carrier relay circuit act to operate an alarm. Is my understanding correct that the worst possible condition the failure of the carrier relay equipment can produce is the tripping out of a line section on a through fault? Has this ever happened?

It would seem that a failure in the tube circuits of the supervisory control equipment at the control point, if it occurred in just the right place at just the wrong time, might cause serious operating difficulties. What are the most drastic consequences which it is supposed might on rare occasions occur? How long would it take to isolate and replace such faulty tubes, etc.?

The performance expected of this project was of such an unusually high caliber, and many of the technical features were so far developed beyond previous practice, that it is no small achievement for these gentlemen to be able to say that this transmission project is living up to their expectations. To single out one item for example, the lightning record of the line is worthy of attention. Here, at last, is a line that "can take it." Three years of lightning, including a large number and variety of recorded direct strokes have not produced a single insulation failure. This is what was expected. True. It is none the less awe-inspiring to contemplate the proved fact.

These gentlemen of the Department of Water and Power of the City of Los Angeles are, indeed, to be congratulated on the results of their labors.

**K. B. McEachron** (General Electric Company, Pittsfield, Mass.): Those who are concerned with the protection of transmission lines from the effects of lightning are naturally much interested in learning of the excellent results obtained with the Boulder Dam transmission line as described by Mr. Cozzens. The experience records obtained add materially to the existing knowledge of lightning. I am especially interested because most of the lightning data obtained thus far have been secured in the East, and yet the results from the Boulder Dam transmission line agree very well in general with what would be expected, based on results obtained in the eastern part of the United States. This tends to support the general conclusion that lightning is not particularly different in the western part of the country than it is in the East. If the general conclusions can be substantiated, it will make the large amount of data already obtained of greater value, since it becomes more widely applicable. There is no doubt but that the severity of lightning storms are related to meteorological conditions, which are of course different in different parts of the country, which consideration would lead one to expect to find variations with respect to localities widely separated. These variations, if they exist, may however be covered up by other variations which have not been recognized.

Mr. Cozzens used a stroke surge impedance of 200 ohms, which, at the time the line was designed, and still is, a value used frequently when making line flashover calculations. I believe that considerable doubt surrounds the use of a surge impedance for a stroke channel, but the results obtained using values ranging from 200 ohms to 400 ohms have been reasonable, and experience seems to show that the answer obtained using such surge impedances is about right.

I do not believe, however, that the mechanism of discharge is at all similar to the discharge of a charged capacitance through a conductor. In the case of outdoor lightning, the cloud consists of charged drops of water or particles of ice separated by an air dielectric. At the time a stepped leader leaves the cloud to progress toward the ground in a series of steps, charges of opposite sign to that of the base of the cloud are accumulated on the ground These charges, usually positive in sign, because the cloud seems to be usually negative, can move in toward the point to be struck with little voltage drop where conducting objects like counterpoises are available for carrying the charges. As the negative leader progresses, requiring often as long as 0.01 second to reach the earth, it produces a space charge around its own channel.

When the downcoming leader is within a few hundred feet of the ground, the increase in field intensity on the surface of the earth is often sufficient to cause a concentration of charge at the point to be struck of a magnitude which forms streamers which may extend several feet from the earth. These streamers increase in length as the downcoming leader approaches, until the leader makes contact, presumably with the longest streamer, after which the return stroke takes place between the earth and the cloud.

McEachron and McMorris ("The Lightning Stroke: Mechanism of Discharge," *General Electric Review*, October 1936) have suggested that the current builds up to a maximum during the time occupied by the step leader in traversing the last few hundred feet from the earth. The maximum current occurs at the time of contact, and as far as the current wave through the stricken object is concerned, the wave tail takes place during the return stroke. If this return stroke fails, as it sometimes does, to reach the cloud, it is possible to calculate the length of the tail, knowing the rate of propagation of the return stroke. On the other hand, if the return stroke reaches the cloud, the length of the tail will be dependent upon the conditions in the cloud. Additional charge may be available, or new regions tapped in the cloud, giving rise to a long tail or to a multiple stroke.

With this conception, the rate of rise of current is dependent upon the amount of charge in the leader and its rate of propagation. The maximum current is dependent upon the amount of charge and its availability on the ground at the point struck. The tail of the wave results from the flow of charge from the earth into the channel created by the leader.

Data are not yet available to support completely the foregoing, but nevertheless sufficient data are at hand to indicate strongly the probability of the mechanism indicated. Propagation data on a large number of strokes are available, and the existence of streamers up from the ground has been identified through photographic evidence. Much remains to be done, and work is actually progressing, which should add materially to the information available as to just what does happen at the instant of contact.

Mr. Cozzens has commented on the presence of corona in the ground around the counterpoise wires. There is no doubt that corona and sparks exist when the potential of the counterpoise is high enough. Impulse tests on ground rods of fairly high resistance earth have shown reductions of the order of 40 per cent in resistance compared to the low-voltage measurements. Corona, coupled with a series and multiple gap effect, no doubt played an important part in this reduction.

Under the heading "Operation and Measurements," Mr. Cozzens discusses the size and character of the burn on the tower gap in relation to the magnitude of the current flowing through the gap. There is no question in my mind but that considerable information can be obtained in this manner. However, I do wish to point out that there is considerably more to this picture than the current amplitude. In the studies of lightning to the Empire State Building (*EE, Dec. '38, p. 493–505*), I describe a type of stroke which I have called "continuing," which is really a d-c arc between the cloud and the ground. In one case, a current of the order of 250 amperes or more flowed for a time of 0.51 second or slightly longer than a period corresponding to 30 cycles of the usual power-frequency supply. This particular stroke had a superimposed peak of 13,000 amperes together with many smaller peaks. These results are obtained from an oscillogram of the stroke.

Laboratory tests show clearly that the type of burn to which Mr. Cozzens referred as resembling a 60-cycle burn can be caused by a continuing stroke. Burns showing beads are not as a rule associated with high-current short-time discharges but with the longer time discharges, which will, in general, be of much lower magnitude, although they may have high superimposed peaks. This situation, of which I have obtained oscillographic evidence in which the explosive effects of high-current short-time discharges are combined with the burning effects of low-current long-time discharges tends to confuse the story to be obtained from burns on gaps, at least in some cases.

Mr. Cozzens also suggests the possibility of multiple strokes moving across a distance of 265 feet from one tower line to the other. Such a possibility seems very remote to me in view of our latest data. The maximum time of discharge of which I am aware is 1.53 seconds obtained in 1937 in New York City. It would require a 118 mile wind and a stroke duration of 1.53 seconds to affect both lines from the point of view of blowing the discharge path from one circuit to the other. Such a combination of high wind at right angles to the line, and of maximum duration, is extremely doubtful. There is one other possible explanation, but it too is not likely to occur. I have photographic records of two multiple strokes which changed their paths on the ground end between successive strokes a distance of several hundred feet, apparently due to change in local ionization conditions. This phenomenon is most unusual, which might be invoked to explain the results obtained by Mr. Cozzens. It seems more likely to me that the strokes were successive in the same storm but not in the same stroke.

**P. L. Bellaschi** (Westinghouse Electric and Manufacturing Company, Sharon, Pa.): One feature which distinguishes this investigation is that Mr. Cozzens has availed himself of a number of suitable and simple devices to measure the lightning currents to the line. From each, one or more characteristics of the lightning stroke are recorded and from the combined recorded effects a more complete appraisal is possible both in regard to the current amplitude, the duration, and also other characteristics of the discharge.

The writer has long advocated that advantage must be taken of all suitable means if lightning phenomena are to be investigated on a comprehensive basis. The magnetic link has shown its usefulness in recording the crest of the current—an important factor to know in lightning protection. Surface burning of metal parts, such as the tower gaps on the Boulder Dam line, and in addition fusion of metal links and other similar means contribute to determine the current amplitude and the nature of the discharge.

For example, test results obtained at Sharon during the past year have established that currents in the order of a few thousand amperes sustained several thousand microseconds produce concentrated fusion effects similar to that in figure 2*B*. As it already had been suspected a few years ago, this fusion apparently results from such current components being present in the discharge of certain lightning strokes. The concentrated arc and sustained arc drop of these current components thus produce fusion effects resembling those of the power arc.

In this connection the photographic studies during the past five years by Doctor B. F. J. Schonland and his associates ("Progressive Lightning—III," *Proceedings of the Royal Society*, September 1937) clearly show that the high current, which results from the main stroke discharging from earth into the established channel and the main branches, takes place in some 100 microseconds. This intense discharge is followed by a sequence of moderate current components extending into hundreds and even thousands of microseconds. The source of these current components seems to reside largely in the cloud and are due to a continuation of the lightning discharge in the cloud proper. While visual accuracy may be questioned, it is apparent to those who have closely observed lightning that some of the prolonged discharges are in the nature of low currents sustained in some instances in the order of one second. In analyzing the fusion effects account must furthermore be taken of multiple lightning strokes.

Tests made on aluminum sheets will illustrate the distinct character of the surface fusion produced respectively by the intense current of short duration and by the moderate current components sustained for a much longer time. Currents of 125,000 amperes having a total duration of some 400 microseconds produced surface burning concentrated in a $^5/_8$-inch diameter circle quite similar to those in figure 1. It is estimated that the metal was fused in the test about 0.005 inch below the surface. Tests made on a 0.035-inch aluminum sheet with a 330-ampere current of 108,000-microsecond duration (interrupted in $6^1/_2$ cycles) burned a $^1/_8$-inch diameter hole practically through the sheet. In addition four smaller spots were fused in the sheet.

**E. H. Bancker** (General Electric Company, Schenectady, N. Y.): There are several items in Mr. Draper's paper that strike me as worthy of comment. The first of these is the great amount of careful preliminary engineering which was done in connection with the transmission line problem for this project. Under the heading "Specifications" Mr. Draper gives an operating time for the protective system that was written into the specifications, without any statement of how and why these figures were reached. It seems to me that it might interest many of you to know that if a relay system having these characteristics had not been available, it would have been necessary to have constructed a third transmission line to carry the same amount of power through short circuits with maintained stability. This is probably an extreme case illustrating the economic benefits that may result from improved relaying. By the expenditure of a few thousand dollars in relay equipment, the cost of a several million dollar transmission line was deferred until a higher load condition was reached.

The second item of interest is the statement under "Specifications" that the protection should be immune to operation on an out-of-step or surging condition. Under ordinary circumstances the balanced current relaying will do most of the fault clearing, but obviously each section must have some form of single-line relaying. It may not be appreciated that in this instance, the ability to refrain from tripping is a most important requirement for the single-line relaying. If this were to trip on the power swings following the operation of the balanced relays, the tie between the Boulder Plant and Los Angeles would be lost. This requirement ruled out as back-up protection for single-line operation even such simple things as time-overcurrent relays, because even they would notch closed on successive power swings. It is rather curious, therefore, that the principal requirement of part of the protective relaying system is not that it shall trip, but that it shall refrain from tripping. This was a performance not obtainable with any other kind of relays, except pilot protection.

The chief item of interest to me in this paper is the operating experience. It is in actual operation that the little unexpected kinks and wrinkles develop and must be ironed out. The experience with the tubes is not unusual, but merely confirms that of other utilities having carrier equipment. Some of the other experiences were rather novel, particularly the operation of the ground relays when a section of line was picked up by closing an oil circuit breaker. Every one knows that the three poles of a circuit breaker do not close at exactly the same instant, but with types of relaying in service and at voltages previously used, the effect of the non-simultaneous pole closing was not noticed in any relay action. In this case the unusually high voltage and length of the line section resulted in a residual current that was big enough, lasted long enough, and was in the right direction to cause the ground relay to operate to trip. The solution of bypassing the high frequency that resulted from these switching operations around the tripping relay coil is merely another example of the high order of engineering that has gone into the design and maintenance of the equipment on the Boulder line.

The methods devised for synchronizing the oscillographs at two stations and tying them in with the closing of a circuit breaker was most ingenious and highly effective. I have seen a number of the records taken in this way and can vouch for the success in recording a large number of electrical quantities at widely separated points with a high enough oscillograph film speed so that individual cycles can be studied and accurate time records of the performance of different parts of the equipment made.

Another interesting item is the use of copper-oxide rectifiers as check valves in trip circuits. As Mr. Draper says, this is probably the first practical use that has been made of this scheme. While it may seem a little thing, again it has considerable economic importance because it permits energizing the circuit breaker trip coils without the wasted time needed to operate an auxiliary relay which would partially undo the good accomplished through the purchase of three-cycle circuit breakers.

In conclusion, I should like to acknowledge publicly the fine spirit of co-operation exhibited by Mr. Draper and his associates during the investigation and correction of the troubles mentioned under "Operating Experience." When users and manufacturers work together with such a fine mutual understanding of each other's problems an amicable and satisfactory solution is reached quickly and easily.

**R. W. Sorensen** (California Institute of Technology, Pasadena): These papers, together with certain other papers included in the symposium, present to the Institute membership the results of almost two years of operation of the present world's outstanding supervoltage power line. The data as presented again exemplify the mastery of electrical phenomena which competent electrical engineers have. In spite of many unusual storm conditions and new features involved in this line, the engineers who planned, designed, erected, and operated it have so completely analyzed all the problems involved and so well anticipated transient outages which have occurred as to make possible this first two years of operation without any very serious interference with the power supply for a great community of people.

When we stop to consider the fact that coupled with all the features of engineering which have been named there was also a change of frequency program involving a change from 50 cycles to 60 cycles for the entire system, we certainly would be remiss if we did not compliment the Bureau of Water and Power staff on its outstanding achievement. In reciting this well-earned tribute we must not fail to note the courage shown by these men in going to a voltage of 287.5 kv when, without additional expense or probably at even less expense, the same amount of power could have been transmitted over 230-kv lines, the construction and operation of which has become more or less standardized.

The lightning protection for the line and the way it has functioned has been so complete and satisfactory that there are few points leading to any discussion. It is interesting to note that a considerable portion of this line—although we generally consider California a nonlightning country—passes through a territory subject to lightning storms, the number of which approximates the average number occurring in many parts of the United States. Indeed the data presented indicate that the severity of these storms is rather high and it would be difficult to overestimate the thoroughness with which Peterson and Cozzens have analyzed the lightning problems and the effectiveness of the measures for guarding against lightning outages which they have included in their line design.

The corona experience on the Boulder Dam line as discussed presents some interesting features in showing a difference between corona loss values as made on sections of line crossing the desert areas and the preconstruction corona loss measurements made in the Ryan Laboratory. Without doubt both sets of measurements are correct and we have before us the striking situation of an increased corona loss in desert areas over that anticipated. I do not think any unexpected corona loss has ever been noticed on the considerable number of miles of 230-kv lines which for years have operated in similar desert areas. There is a possibility that certain sections of the 230-kv lines which traverse desert areas to some extent might show corona loss over that found in nondesert areas, which simply has not been observed because, as the authors have pointed out, the measurement of corona loss on an actual transmission line traversing many kinds of country at different altitudes is no easy matter and none of the lines—the one under discussion or the 230-kv lines which I have in mind—has any great amount of kilowatt-hour corona loss. On the other hand, it may be that the conditions which are essential for the operation of 287.5-kv lines; namely, large diameter conductor and this higher voltage, introduce factors which are not so noticeable at 230 kv and hence do not demand the attention at 230 kv which must be given them at perhaps 287.5 kv and higher—should we in the future raise our transmission voltages to some higher value.

It is interesting to comment here that 10 years elapsed between the installation of 150-kv lines and 230-kv lines—the maximum potential up to the installation of the 287.5-kv lines—and that 15 years have elapsed since the 230-kv lines went into operation; and now we have 287.5-kv lines.

To return to the unexpected excess corona loss on the desert, I will just present for our consideration a report of my observations concerning corona phenomena which may be noted any time in the high-voltage laboratory at the California Institute of Technology. We have installed in the laboratory a smooth bus $3^{1}/_{2}$ inches in diameter. With voltages approaching 300 kv applied to this bus, we note that while the complete bus does not go into corona, trees or brushes of corona and sometimes quite definite brush discharges will be noted at points along the bus. These discharges seem to start at places of very slight irregularity or dust accumulation on the bus, even though we sometimes think we have the bus all clean. The difficulty of keeping the bus free from these discharges has led us in our laboratory experiments to use for most of our conductor pieces of chain such as are used for window weights, door checks, etc. Naturally these pieces of chain go into considerable corona at voltages much lower than the initial corona on the $3^{1}/_{2}$-inch bus. The corona formed along the chain, however, soon builds up an ionized layer of air around the chain which serves as a shield around the chain and seemingly holds the total corona loss to an amount no more troublesome than the corona which forms on the large bus. In fact, the corona along the chain seems to be limited almost entirely to regular corona glow rather than the brush discharges which occur on the bus. We have never gotten sufficiently interested in the phenomena thus observed to make any measurements. These phenomena, however, in connection with the unexpected phenomena mentioned in the paper lead me to suspect that small irregularities on large conductors, particularly smooth-surfaced ones, may result under some conditions in corona phenomena quite annoying and difficult to eliminate. Whereas the 230-kv lines which have come under my observation, and which are all stranded-conductor lines, as I have stated, have never shown this phenomenon on the desert to an extent which has led us to believe there is any difference in corona loss on the desert and in the laboratory which cannot be accounted for by the usual things which affect corona; namely, humidity, temperature, barometric pressure, conductor surface irregularity, etc.

**Bradley Cozzens:** The discussions presented by K. B. McEachron and P. L. Bellaschi always add new or confirming facts to any paper because of the very intimate and continuing contact that these men have with lightning studies and associated phenomena. Specifically referring to Mr. McEachron's comments: we too, are pleased to have data indicating that the magnitude of current and possibly voltage encountered in western lightning is not materially different from that of eastern lightning, for it was upon much of the data gathered regarding eastern storms that the lightning design of the Boulder Dam lines was based. From what observation we have been able to make in the few years of construction and operation it appears that the number of strokes per storm may be materially less than for the eastern locations, possibly due to the higher average cloud height and also the smaller amount of actual water vapor involved in any one average storm.

As mentioned in the paper, surge impedance values can be calculated that show a wide variation in magnitude depending upon assumed conditions. We agree heartily with Mr. McEachron in his criticism of the use of a lightning stroke as being a path of definite surge impedance short-circuiting the condenser between the cloud and earth. It is indeed a much more complex circuit. The use of the 200-ohm value, however, gives a design that will cope with some of the most severe lightning strokes while the higher values would of course be more representative of the less intense discharges. Perhaps with further accumulation of information Mr. McEachron or Mr. Bewley, on whom we lean quite heavily for methods of computing lightning phenomena, may evolve methods that will take into account the resistance or impedances between the various charge masses in the cloud to account for the relatively slow build up of the current in the streamers. Such information might modify greatly the present methods of computation, but while we realize that present methods are not rigorous, they are still the only methods available to most of us.

Mr. McEachron mentions that the maximum current is dependent upon the availability of the charge on the ground. The use of the counterpoise makes this charge easily available from a much larger area than normally. It is still questionable whether an extensive counterpoise system may not some day feed such heavy currents into the lightning strokes that the voltage drop in and immediately adjacent to the tower will become a factor. This would be first evidenced on the lower voltage lines.

It is indeed gratifying to have definite confirmation of the formation of corona around the buried counterpoise wires. Our only information, other than reported reductions in measured surge impedance with the application of high surge voltages, was the observed phenomena of corona forming about a conductor in salt water when surged with high impulse voltages. This corona area around the counterpoise was used in the design computations and with Mr. McEachron's comments we are more certain of its justification.

While we had no oscillographic records of the duration of any of the lightning strokes to the Boulder Dam lines, yet mention is made in the paper that from the types of burns observed on the counterpoise gaps, some were probably of short duration while others must have been the result of long-time low-current discharges or many multiple strokes occurring in rapid succession. Mr. McEachron's recently recorded data on the long-time low-current strokes confirms the assumptions mentioned in the paper. Knowing this now to be the case, the information from the counterpoise gaps will be much more valuable for from observing many of them it is possible by careful observation to detect multiple discharges, with appreciable time interval between them by the overlapping of the burned areas. The single-discharge high-current value can be detected relatively easily, and the long-time low-current value also can be identified. Of course these are not instrument measurements and should not be treated as such, but they will add information I feel sure.

Mr. McEachron's comment on the impossibility of a multiple stroke to follow the same general path and travel the 265 feet between tower lines in his maximum observed time of 1.53 seconds is of course correct. However, the change of path for the lower portion of strokes does not seem to be quite as uncommon as indicated. A very beautiful example is given in the United States Department of Commerce Bureau of Standards publication No. 95 on protection of electrical circuits and equipment against lightning. Figures 1 and 2 show the still and moving film records of a multiple stroke in which the lower section entirely changed path for one or possibly more of the discharges. Again we have no definite proof that this was the case for the strokes involving both of the Boulder lines, but as mentioned previously, the desert storms are usually high clouds and are moving rapidly so that successive discharges usually progress with the storm except where the storm clouds are being blown over a mountain area. It is felt, therefore, that strokes to both circuits in a single area come either as this diverted multiple discharge or within a very short time interval.

We greatly appreciate Mr. McEachron's comments on this paper.

The comments of Mr. Bellaschi add further evidence by laboratory tests indicating that burns that result in appreciable fusion of the metal must be the result of long-time low- or moderate-current discharges. The few values mentioned by Mr. Bellaschi covering some of his recent tests indicate that the study of the area and volume of burned metal as a function of the current and time involved is just begun if it is to be used extensively as an indication of lightning current. It, definitely, is a rough means of indication if not interpreted too rigorously.

**J. D. Laughlin:** Discussions and questions as asked by Abe Tilles bring out points and information additional to that contained in the original paper, as the reader may see the subject from a different angle to that presented by the writer.

The following discussion, in answer to Mr. Tilles' questions relative to starting generators at Boulder and energizing the Boulder transmission line and his questions relative to the consequences of tube failures in the supervisory control equipment, gives some additional information pertaining to the operation of the transmission line not included in the original papers.

Starting a generator from the condition with the butterfly valve closed and all auxiliaries shut down normally requires approximately 15 minutes to put the unit on the line. Ten minutes of this time is used in opening the butterfly valve and checking the generator auxiliaries. Before starting any unit, all auxiliaries are operated manually, then shut down and set for automatic operation. Included in the auxiliary check are devices for supplying bearing oil pressure, governor oil pressure, generator cooling water and transformer cooling water, generator field breaker, overspeed devices, and position of the butterfly valve. When these checks are completed and reported to the operator in the control room, he closes the master starting switch. Within two minutes all auxiliaries have been started automatically and the generator is up to full speed. The operator then adjusts the generator voltage and selects the oil circuit breaker to be used for synchronizing. Actual synchronizing and closing of the circuit breaker is done automatically. From the time the generator is up to full speed until it is on the line requires approximately two minutes. If the butterfly valve is open and the scroll case is full of water and it is desired to get a machine on the line quickly, this can be accomplished in approximately four minutes by omitting the auxiliary inspection.

The generators are always synchronized to the lines, using oil circuit breakers on the generator busses. Automatic synchronizing equipment is used for putting all machines on the line for normal operations. Manual synchronizing is used only on special occasions, as for tests or when some equipment is out of service.

When both circuits are de-energized and it is desired to connect Boulder to the system at Los Angeles, two generators are synchronized on the low voltage bus and adjusted for one-third normal voltage. The line is then picked up, one 90-mile section at a time without any further adjustment of the generator fields. When all six sections are energized but not connected to the system, the generator voltage at Boulder is approximately 75 per cent of normal, and at the Los Angeles end of the line the voltage is 100 per cent of normal. The line is then synchronized with the system at Los Angeles. The synchronous condensers for voltage regulation at Los Angeles are connected to transformer banks fed from the 132-kv bus and may be put on the system either before or after the Boulder line.

A second method has been used for picking up the lines but it is more hazardous to equipment than the one described above. For this method, all circuit breakers on the lines are closed except those that connect the lines to the system at Los Angeles. Two generators are brought up to normal speed and connected to the lines without any field excitation. The generator fields are then closed and excitation is increased slowly until normal voltage is obtained at the Los Angeles end of the line. This method is not used due to the difficulty in regulating generator excitation so as to maintain synchronizing current between the machines and not get the line voltage too high. If one circuit is energized and one de-energized, and it is desired to put the second circuit into service, at least two generators must be on the line at Boulder. The dead line is then picked up one section at a time starting from the Boulder end.

Regarding the failure of tubes in the supervisory control equipment, the most serious result that could occur from a tube failure would be a failure of a nature that would overload and damage other equipment in the carrier-current circuits, such as condensers, transformers, or wiring; however, the circuits are protected with fuses in such a manner that this condition is very improbable. Usually when a tube burns out it stops the transmission or reception of a code and prevents the completion of the intended operation. In no case could it cause a false operation. When such a condition occurs, it is immediately detected at Boulder. The operator can usually determine at which station the failure occurred by noting at what point in the code sequence the equipment stops. He then calls the attendant at the station in trouble by telephone and has him check his equipment. The replacement of a faulty tube is a matter of a few minutes after it fails. The failure of a tube in any station except at Boulder does not interfere with the operation of the balance of the supervisory control equipment. Operations can still be performed at the other stations, and indications received. In case of a tube failure at Boulder, the entire equipment is out of service, since codes from all other stations must be recorded and checked at Boulder before the intended operations can be completed.

**L. L. Draper:** I would like to express my appreciation for the very generous comments of Mr. Tilles and Mr. Bancker on this paper and will endeavor to answer Mr. Tilles' questions regarding the relays in a general discussion rather than trying to answer each question individually.

Each section of the third circuit will be equipped with carrier-current pilot protection like that in use on the present circuits. With this type of protection each section of each circuit is protected as an individual unit and the worst possible condition that the failure of carrier to be transmitted or received can produce is faulty tripping of that particular section upon the occurrence of a through fault condition. As mentioned in the paper the carrier-current pilot protection used is considerably faster than was anticipated at the time the specifications were written and is sufficiently fast to meet the required clearing time under all conditions without any additional speeding up.

As Mr. Tilles has stated complications arise in a scheme of high-speed balance current protection for three parallel lines. This is particularly true with the ring arrangement of six oil circuit breakers as will be used at Boulder, Silver Lake, and Victorville. For this reason and also because balance current protection cannot be applied to the section of the third circuit between Victorville and Los Angeles consideration is being given at this time to other types of protection that might be used as a second line of defense on these lines. The final decision as to the second set of protection equipment on these lines will be to use the overall scheme that will give the least probability of an undesired separation between Boulder power plant and the Los Angeles system due either to failure of the relays to trip a faulted line section or faulty operation of the relays on line sections that are not faulted.

Mr. Bancker has brought out the principle reason for the short operating time requirements of the specifications in so far as this line is concerned, however, there are other well-known benefits to be gained by fast clearing of faults one of which was very well illustrated by the system load dispatchers report of the two faults that occurred on these lines on March 2, 1938. In each case the report contained the very terse statement "No disturbance to voltage." Actually of course there was a disturbance to the system voltage, but of such short duration that from all practical standpoints the statement was absolutely correct.

Mr. Bancker attributes the high-frequency transient currents, that caused trouble with the ground relays, to the nonsimultaneous closure of the oil circuit breaker poles and while this was probably a contributing factor, I believe that the predominating factor in the production of these high-frequency currents was the point on the voltage wave at which individual poles of the breaker closed and that they would be produced on these lines, even with simultaneous closure of the breaker poles.

**Wm. S. Peterson:** The engineers who have been associated with the Boulder Dam transmission line development deeply appreciate the interest shown in this project and are sincerely grateful for the many fine comments that have been made in discussing this group of papers.

In reply to Mr. Tilles' question regarding the alteration of sending-end voltage as the load varies, it can be stated that the operation is very closely in accord with operating under the condition for minimum loss. The normal voltage of the generator is 16,500 volts to produce 287,500 volts at the sending end of the line. This voltage is used when delivering approximately 200,000 kw at the receiving end of the two circuits. For delivering the rated output the voltage is increased to 17,000 volts and for very light loads, under 75,000 kw, the voltage may be reduced to 15,500 volts. This change is made by manual adjustment of the regulator settings. This type of operation requires slightly less synchronous-condenser capacity than does fixed-voltage operation.

Mr. Tilles asks about the location of the third circuit. For two-thirds of the way, it is parallel to the existing circuits and is about 265 feet from such circuits. From Victorville to the Department's receiving station *E*, the line diverges from the existing line going directly west instead of southwest.

Doctor R. W. Sorensen has made the statement that the same amount of power could have been transmitted, without additional expense, at 220 kv.

In such comparisons account must be taken of the type of service, or the conditions, on which the line is rated. Two 220-kv circuits of similar length if operated within the criteria set up for a steady-state stability basis of operation would have about the same rating as do the two 287.5-kv circuits on a transient stability basis. However it was the purpose in building this line to achieve a reliability of transmission equivalent to that given by a local steam-electric generating station. It therefore had to be rated on a transient stability basis for withstanding, without loss of synchronism, a two-phase-to-ground fault at the worst point on the system, drop a section of line and still have a margin of 25 per cent as a safety factor. Calculations show, that, in order to achieve the same rating with 220 kv, it would require the use of three circuits. Three circuits of 220 kv of a given standard of construction are more expensive than two circuits of 275 kv of a similar standard. Economy in obtaining reliability dictated the choice of 275 kv.

Turning to the corona discussion by Doctor Sorensen, I am inclined to agree with his observation that it may not have been observed because measurement of loss on actual lines is difficult to make and it takes accurate measurements to determine the differences under discussion. The phenomena has been identified as having relation to locality, so it is possible that other lines are in areas not affected by the same factors as are present in some places along the Boulder lines.

In making the corona-loss measurements at Victorville the voltages for the conductors under test were carried as low as 220 kv. For these low voltages, the "voltage shifts" in the corona-loss curves for the desert area from those run at Stanford on the same conductors are of the same order of magnitude as found at the higher portion of the loss curves. These measurements were on conductors having diameters of 1.25 and 1.4 inches for the smooth surface type and 1.4-inch diameter for the stranded type. It is reasonable to suggest that if the smaller diameter conductors associated with 220-kv lines had been tested at the same location that a similar shift would have been found and that it would have given appreciable loss differences because 220 kv would have been nearer the "knee of the curve" for such conductors than those tested.

# The Electric Strength of Air at High Pressure

By H. H. SKILLING
MEMBER AIEE

**Synopsis:** Experimental data show that the strength of compressed air as an insulator increases with pressure until a critical value is exceeded. At higher pressures the sparking voltage fails to rise, and may even drop. The maximum voltage and the critical pressure are largely dependent on the shape of the electrodes of the spark gap.

OVER thirty years ago work was done by Ryan[1,2,4] and his student, Ekern,[3] to determine the electrical strength of air at pressures of many atmospheres. It was discovered that the voltage required for sparking between points bears a roughly linear relation to the air pressure until the voltage has risen to approximately ten times that required for sparking between the same points, at the same spacing, at normal atmospheric pressure. A maximum voltage is reached at an air pressure of between 100 and 200 pounds per square inch. As the pressure is further raised, the sparking voltage does not rise correspondingly—in fact it drops somewhat if sharp points are used, and then at still higher pressure (above 400 pounds per square inch) the voltage rises slowly with pressure.

More recent work has been done by a number of scientists: some of this work is summarized by Whitehead.[11] The latest to be published is by Goldman[12,13] of the Union of Socialist Soviet Republics. Goldman's work will be mentioned again in a later paragraph.

Renewed interest in the electrical properties of air at high pressure has appeared recently. This may be traced to the present use of compressed gas as insulation in radio transmitter condensers, in electrostatic generators, and its proposed use in high-voltage power cables. The present paper is a report of an experimental study of the subject.

The chief contribution of the present paper is a study of the effect of the shape and material of electrodes. In previous investigations Ryan and Goldman worked with points, and Goldman, Amyashi, and others, worked with plane surfaces or surfaces with large radius of curvature. It is believed that no one has heretofore investigated both of these types of electrodes and also the intermediate region of electrodes of various radii of curvature. In the investigation of electrode material, electrodes of copper, iron, and zinc were used.

The present investigation also gives assurance that the results are not seriously influenced by distortion of the electric field, brought about by proximity of the walls of the enclosing chamber. Previous work has been done in pressure chambers of relatively small size.

## Apparatus

The pressure chamber in the present work has an inside diameter of six inches. This permits the study of longer gaps and larger electrodes than were used by Ryan, including electrodes of spherical and cylindrical form. However, the increased diameter of the test chamber makes it advisable to use a relatively low maximum air pressure, and since the most essential and characteristic sections of Ryan's curves appeared at pressures below 300 pounds per square inch, the present apparatus was designed for that pressure. Glass and porcelain insulation is used, and voltages lie in the same range as that studied by Ryan.

The outside of the air pressure chamber is shown in figure 1. Two sections of six-inch steel pipe are separated by a sheet of glass, and the cylinder thus formed is closed with a six-inch extra-heavy cast-iron blind flange at each end. The sheet of glass is 14 inches square, with a four-inch round hole in the center. This cylinder, with the insulating sheet of glass and the two blind flanges, occupies a central position in figure 1; it is the test chamber, and air is pumped into it through a pipe inserted in the lower flange.

The cylinder is made to retain air under pressure by being clamped between a pair of eight-inch I-beams, as shown in figure 1. Just above the pressure cylinder is seen a cast-iron spacer block, and between that and the upper beam is a small steel roller for equalizing forces. By tightening screws beneath the standard suspension-insulator units at the ends of the beams, the beams are drawn together. This exerts an axial force on the cylinder, and a compressive force on the glass of about 10,000 pounds. The insulator units, together with the glass sheet, completely insulate the upper beam and the upper half of the cylinder from the lower beam and the lower half of the cylinder. Leads from a high-voltage transformer are connected to the two beams.

Within the pressure chamber is the small frame shown in figure 2. The vertical members of the rectangular frame are insulating, and electrical connection is provided from the top and bottom of the frame to the upper and lower blind flanges, respectively. Some of the electrodes used appear in the photograph. Sharp points, spheres, and cylinders were used, of different materials, and with various sizes and spacings.

Sixty-cycle alternating voltage was used in all tests. A 300-kv, 150-kva transformer was used to supply the test voltage. Power was supplied to the transformer from either the sine-wave generators of the Ryan Laboratory or the commercial supply mains; even in the latter case the wave form does not vary from a sinusoidal wave by a significant amount. Voltage was adjusted by variation of the generator field (when the generator was used) and by means of an induction voltage-regulator in the transformer primary circuit. The voltage was measured by means of a tertiary voltmeter winding, known to be correct.

The location of the spark within the chamber, and the relative intensity of the spark, could be observed through the insulating glass sheet. In this way it was known that the spark occurred between electrodes, as desired. In one test the spark took place, due to moisture, along the surface of the glass within the apparatus; this was immediately detected and corrected. It was not possible, however, to see anything of the form or nature of the discharge.

## Results

Experimental results are plotted in figures 3, 4, 5, and 6. These curves indi-

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[1] For all numbered references, see list at end of paper.

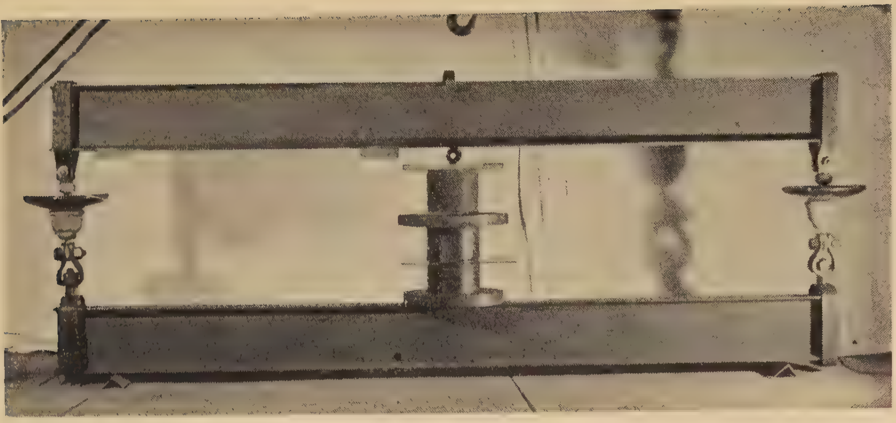

**Figure 1. The test chamber for holding compressed air**

cate average sparking values, each measurement being repeated five to ten times. As an indication of the consistency of results it may be well to consider a sample of the work in detail. Curve *A* of figure 5 is drawn through a number of small circles which represent the average experimental points. At each pressure used the sparking voltage was measured some five or ten times, and the average value is marked by the circle. Individual measurements of voltage were likely to vary by as much as ten per cent; for example, the point on curve *A* at 290 pounds per square inch pressure represents an average of eleven voltage readings that varied from 37.8 to 41.0 kv. Despite this variation of individual measurements, the average values are consistent and reproducible from time to time.

When the electrodes are sharp points, as in figure 3, a maximum value of voltage is evident at about 100 pounds pressure. As pressure is increased from 100 to 150 pounds, voltage for sparking declines. At higher pressure the voltage may or may not rise again, depending on sharpness of the points; at pressures above 100 pounds the voltage required for sparking is greatly increased by dullness of the points (see figure 6). These results are similar to those obtained by Ryan;[2] Goldman,[12] producing sparks between a pointed electrode and a plane, gives voltage-pressure curves of the same shape but with 30 to 50 per cent lower voltage values.

Sparking voltage values in the high-pressure range are erratic compared to sparking voltages at pressures below 100 pounds. This suggests a different mechanism of spark formation. Also, in the higher pressure range there were almost invariably, discharges between electrodes at voltages five to ten per cent below the "sparking voltage" plotted in the curves. These preliminary discharges were of momentary duration, and failed to initiate a complete breakdown of the gap. (They sometimes carried enough current to actuate a circuit-breaker in the primary circuit of the high-voltage transformer, so that it chattered but did not trip. The plotted "sparking voltage" is the voltage at which the breaker opened. The height of the curves obtained would vary a few per cent with changes of the speed and setting of the breaker. Therefore, for consistent results, the setting was kept always the same.)

In figure 4 are shown curves of sparking voltage for one-inch-diameter spherical electrodes (steel balls from a ball bearing). Considering the spacings used these are large spheres, and the electric field between them in the region of nearest approach is almost uniform. (The maximum field strength is increased three per cent by curvature of the spheres.) Since the electric field near a sharp point is highly divergent, the pointed and spherical electrodes represent opposite extremes of electrode configuration.

It will be seen from figure 4 that between spherical electrodes the sparking voltage increases with pressure in a more or less linear fashion until a pressure of about 250 pounds is reached. At higher pressures the sparking voltage remains constant, within the experimental range. The effect of pressure above 300 pounds on the sparking voltage could not be determined because of limitations of the apparatus. Other investigators[1,11,13] show similar flattening of the voltage-pressure curve, but at higher values of voltage and pressure. Although all investigators show the flattening effect, there is little agreement as to the voltage and pressure at which it occurs. There is the possibility that the flattening of the curves of figure 5 is merely a point of inflection, and that voltage would again rise with large increase of pressure. The author, interpreting sparking at high pressure as due to field current, believes that different investigations give different results because of unlike conditions of electrode surfaces. The importance of this factor will be considered later.

Figure 5 shows the gradual change of form of the voltage-pressure curve as the radius of curvature of the electrodes was reduced. All of the curves of that figure apply to spark gaps of 0.05-inch length. Curve *A* was obtained with large steel spheres ("large" in the sense that the radius was nearly ten times the gap length). The practically identical curve *B* is for cylindrical zinc surfaces with large radius of curvature. Curve *C*, for small steel spheres, with radius approximately equal to the spacing between them, is noticeably different; and curve *D*, obtained with electrodes of copper wire spaced nearly twice their radius, shows further difference of the same nature. As the radius of curvature is decreased the curves are less sharply flattened at 250 to 300 pounds pressure, and the voltage required for sparking in that pressure range is reduced. Curve *E*, for a smaller iron wire, and curve *F* for a smaller copper wire, are further altered in the same manner. Curve *G* represents two sets of data that were practically identical: they were obtained with electrodes of copper wire in one case, and with blunt steel points in the other. The radius of the copper wire was $^1/_{10}$th the gap length (0.010-inch diameter); the steel points as viewed under a microscope were rounded at the tips due to the original sharp point having been burned to a blunt end about 0.015 inch across.

The same dull points were used for one of the curves of figure 6; the spacing between them having been increased to 0.30 inch. The two other curves of that figure correspond to increased sharpness of the same points, the "sharp" points being freshly ground and showing, under the microscope, the marks of the abrasive wheel. These three curves continue, in a sense, the series of curves of figure 5, for they complete the transition from "large" spheres to sharp points. Through the entire series the voltage maximum at about 250 pounds pressure becomes less apparent, and a maximum at about 100 pounds pressure appears as characteristic of sharp points. Curve *G* of figure 5 is the first to show a pronounced hump in the 100-pound region.

The various electrodes used for obtaining the curves of figures 4 and 5 are of such simple geometrical shape that the surface electric gradient corresponding to breakdown could be computed. (The electrodes for curve *G*, however, were omitted because corona probably produces space charge about them before sparking voltage is reached.) The maximum surface gradients obtained, corresponding to the flattened parts of the curves at high air pressures, are as follows:

| | Maximum Gradient for Sparking (Crest Kilovolts per Centimeter) |
|---|---|
| Gap length 0.05-inch between: | |
| Steel spheres, 1-inch diameter | 450 |
| Steel spheres, 0.125-inch diameter | 540 |
| Copper wires, 0.063-inch diameter | 510 |
| Iron wires, 0.041-inch diameter | 470 |
| Copper wires, 0.025-inch diameter | 530 |
| Zinc, radius of curvature 0.5 inch | 450 |
| Gap length 0.017 inch between: | |
| Steel spheres, 1-inch diameter | 550 |
| Gap length 0.075 inch between: | |
| Steel spheres, 1-inch diameter | 450 |

Three electrode materials were used. They were copper, iron (and steel), and zinc. Zinc was used because its low work function contrasts with those of copper and iron. Steel and zinc surfaces gave almost indistinguishable voltage-pressure curves. The average of the maximum gradients for copper is a little higher than the average for iron (520 kv per centimeter, compared to 490 kv per centimeter) but this difference is probably not significant. The author's conclusion is that electrode material has little if any effect in the impure state in which it must necessarily exist during electric discharge in compressed air.

## Discussion

A dash line, *H* in figure 5, is drawn to indicate the voltage that would be required for sparking if Paschen's law were valid in this pressure range. Paschen's law expresses breakdown voltage as a function of the product of air density and linear dimensions of the gap,[5] and therefore implies that ionization results from impacts of electrons (or ions) that have been accelerated in the gas.[10] It is seen that the law fails to apply at pressures of several atmospheres, and breaks down utterly at about twenty atmospheres. There can be little doubt that the reason for this anomalous behavior is that a source of ionization which is relatively ineffective at low pressure becomes predominant at high pressure. Moreover, the source of ionization that is predominant at high pressure appears to be nearly or entirely independent of pressure. It seems therefore that sparking at high pressure derives most of its ions or electrons from a source that is independent of the gas in the gap.

Field current, or cold-emission current, is quite commonly found to flow between electrodes in high vacuum when the potential gradient is of the order of magnitude of half a million volts per centimeter.[6,7] Residual gas about the electrodes takes no part in this phenomenon, for the mean free path of electrons in the gas may be many times the gap length. The gradient required for field current is greatly dependent on the surface conditions of the electrodes, the necessary gradient being raised by a factor of two or three or more when the surfaces are polished and de-gassed.

Field current can thus appear between electrodes in vacuum when there is so little gas that it plays no part in the discharge. It seems quite reasonable that field current can also appear between electrodes in high-pressure gas, the gas being so compressed that it takes no part (or only a secondary part) in the discharge. If the mean free path of electrons in the gas is so short that an electron will rarely attain ionizing velocity even though the gradient is raised to the high value required to produce field current, then field current may be expected to flow. This is the most probable cause of the electric breakdown that occurs at high pressure between large, smooth electrodes. It has been so accepted by Ryan and Goldman.

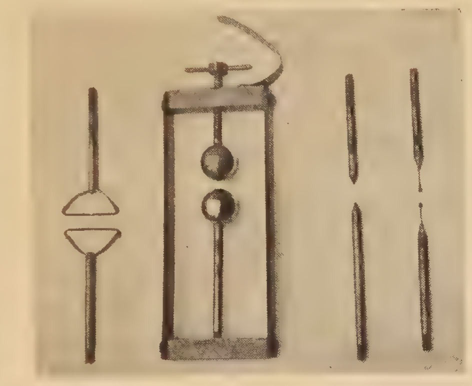

Figure 2. Some of the spark gaps tested

Ryan, in 1911, wrote,[1] "When the stress delivered from the metal electrode surface to the adjacent zone of gas is great enough some of the free electrons in the metal will de detached from the electrode and will migrate through the gas to the anode." Goldman, in 1938, agreed,[13] saying, "Starting from a certain pressure the mechanism of gas puncture is altered. Impact ionization no longer plays a predominant part. With those fields as are obtainable at high voltages, electrons may be torn out from the cathode by the action of the field."

It must be understood that there is no proof that the anomalous sparking voltages at high pressure are due to field current, but there is evidence to support such a belief. The best evidence is that in those cases for which field strength can be computed, the electric field just preceding sparking is of the right order of magnitude to give plentiful field current. Work in vacuum shows (as mentioned above) that an electric gradient of the order of magnitude of 500 kv per centimeter will draw appreciable field current from a metal surface that has not been carefully cleaned, de-gassed, or polished. Compton and Langmuir say,[6] "The past history of the surface has a very great effect on the field strength needed to draw electron currents," and Millikan and Eyring[7] give values varying from 400 to 1,100 kv per centimeter as producing appreciable electron currents from a tungsten filament. Compton and Langmuir found that surface impurities were extremely important, and after saying that "Field currents are obtained much more easily from surfaces covered with adsorbed films of electropositive materials," they report that the result of one test "suggests that traces of alkali metal escaped from the glass and are held by a monatomic oxygen film on the tungsten."

In view of the extreme sensitivity to surface condition it is not surprising that experiments in high-pressure air give breakdown at different values of gradient. It was shown in the preceding table that the gradient believed to produce field current in the present work varied from 450 to 550 kv per centimeter. Goldman obtains a value[13] for a gap of practically the same dimensions, of 730 kv per centimeter in nitrogen, and Amyashi[11] gives data indicating a maximum gradient of about 800 kv per centimeter in both nitrogen and air. All these values are well within the range of gradients determined by work in vacuum. It is evident that when a metallic surface is being subjected to electric discharge in an atmosphere of compressed air it can remain neither highly polished, chemically clean, nor de-gassed. Traces of alkali metals will no doubt always be present. Probably, therefore, the production of field current will depend far more on the presence of unavoidable impurities than on the material of the electrodes. This is consistent with experimental data.

It should be mentioned that it is only in the region of flattening of the pressure-voltage curve that different investigators disagree. When the voltage is less than half that of the flat part of the curve

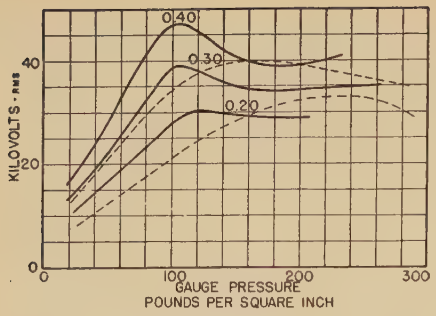

**Figure 3. Sparking voltage between points at various spacings**

Length of gap in inches is marked on curves. Dash lines show Ryan's results for comparison at the two shorter spacings

there is agreement between the present work and that of Goldman and of Amyashi, and between all three and Paschen's law.

The production of electron current by high surface gradient, like the production of electron current by impact ionization, commences gradually and then increases rapidly with increasing applied voltage. Field current in vacuum has been found[6] both theoretically and experimentally to be related to gradient by the equation

$$j = aE^2\epsilon^{-D/E}$$

wherein $a$ and $D$ are constants, $j$ is current density, and $E$ is electric field strength. It is evident that field current is negligible at low values of voltage and that, as current becomes appreciable, it increases tremendously with a small increase of voltage.

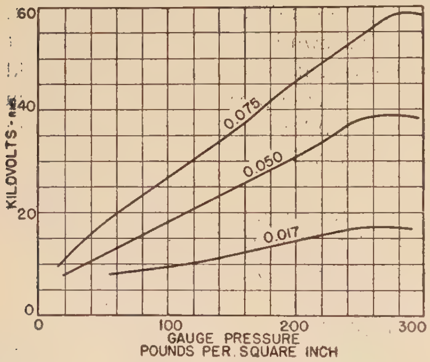

**Figure 4. Sparking voltage between spheres of approximately one-inch diameter, at various spacings**

Length of gap in inches is marked on curves

The electrons of field current, once released into the gas between electrodes in high-pressure experiments, will travel from cathode to anode and will multiply themselves by impact ionization as they go. Even a small supply of field-current electrons will thereby disturb the normal mechanism of sparking in gas, and this may account for the reduction of sparking voltage below that indicated by Paschen's law at intermediate pressures (see, for instance, figure 5). As pressure is increased, and the surface gradient preceding sparking becomes higher, the effect of field current on the spark becomes more pronounced, until finally it is the controlling factor and breakdown voltage is thereafter independent of pressure. The formation of a spark by means of field current probably includes intense heating of a very small spot on the cathode.

## Shape of Electrodes

Experimental data may be considered in four classifications, with indefinite intermediate regions. The four basic categories are:

1*A*. Spark due to ionization of gas; not preceded by corona discharge.

1*B*. Spark due to field current; not preceded by corona discharge.

2*A*. Spark due to ionization of gas; preceded by profuse corona discharge.

2*B*. Spark (see below) preceded by profuse corona discharge.

These classifications correspond to the following physical conditions:

1*A*. Flat or rounded electrodes; low pressure.

1*B*. Flat or rounded electrodes, high pressure, or pointed electrodes in very high pressure.

2*A*. Sharp-pointed electrodes, not close, low pressure.

2*B*. Sharp-pointed electrodes, not close, medium pressure.

Characteristic of classification 1*A* are the curves of figure 4 at pressures below 100 pounds. No explanation is needed, for this type of sparking is that of spheres in open air. These same curves at pressures above 250 pounds illustrate action of type 1*B*: the field strength at the sphere surface rises with increasing voltage until emission of electrons produces field current in sufficient quantity to appear as a spark.

The curves of figure 3, at pressures below 90 pounds, represent sparking of the 2*A* type. This is the customary mechanism of sparking between points in free air.[8] The same curves at pressures of 120 to 150 pounds, and possibly higher, illustrate the 2*B* mechanism of sparking. This requires further consideration.

One is inclined to attribute flattening of the voltage-pressure curves for pointed electrodes, as in figure 3, to the effect of field current emitted from the point. Goldman and Wul's results,[12] however, indicate that such is not the case. Working with direct voltage applied to a gap between one pointed and one plane electrode they found that the typical shape of the a-c voltage-pressure curve (as in figure 3) is reproduced when the pointed electrode is positive, but with the point negative the sparking voltage is higher and continues to rise with pressure through the experimental range (up to 200 pounds pressure). This indicates that the action that causes sparking voltage to diminish as pressure rises must take place at or about the *positive* point, and it clearly cannot be the emission of electrons. Accepting the data of Goldman and Wul, one cannot do better than to accept also their explanation that the anomalous sparking voltage between *points* is due to high concentration of space charge, which, in turn, is the result of low ion mobility in high-pressure gas. This is the 2*B* type of action.

When pressure is further increased the extent of the corona that precedes sparking is curtailed so greatly that the action enters an intermediate region between 2*B* and 1*B*, and at the very high pressures used by Ryan[1] it appears that a

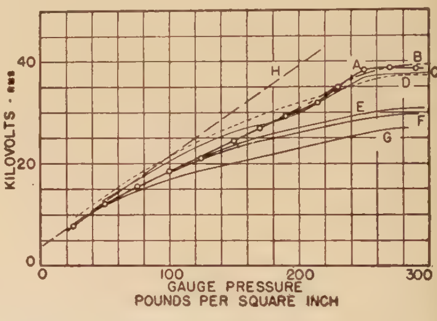

**Figure 5. Sparking voltage between various electrodes, gap length in each case being 0.05 inch**

Electrodes were:

*A*. (Heavy line with circles to indicate average experimental voltage values) Steel spheres, 0.933-inch diameter

*B*. (Dot-dash line, practically coincident with *A*) Zinc cylindrical surfaces, radius of curvature 0.5 inch

*C*. (Light line) Steel spheres, 0.125-inch diameter

*D*. (Dotted line) Copper wires, 0.063-inch diameter

*E*. Iron wires, 0.041-inch diameter

*F*. Copper wires, 0.025-inch diameter

*G*. Copper wires, 0.010-inch diameter, and also points with blunt tips about 0.015 inch across

*H*. Paschen's law (for plane surfaces, extrapolated from low pressure region) fully 1*B* type of action is attained even between sharp needle points.

The curves of figure 6 show varying degrees of similarity to the typical behaviors 2*A*, 2*B*, and 1*B*. With blunt points the maximum voltage at about 100 pounds pressure tends to disappear, while the maximum at about 300 pounds becomes more prominent.

## Conclusions

1. Sparking voltage in air rises as air pressure is raised above atmospheric, but a maximum value is reached. As pressure is further increased, sparking voltage remains constant or becomes less. Maximum sparking voltage is greater than sparking voltage at atmospheric pressure by a factor of five to ten, depending on the electrode configuration.

2. No difference was observed between iron, copper, and zinc as electrode materials.

3. The form of electrode is very important. Electrodes that permit corona before sparking behave quite differently from those that do not.

4. If there is no corona preceding sparking, maximum voltage is reached at 18 to 20 atmospheres pressure (or higher, according to other investigators).

5. If there is corona preceding sparking a maximum appears in the sparking voltage at 7 to 10 atmospheres pressure, and another maximum appears at 20 atmospheres or higher.

6. Sparking between smooth electrodes at high pressure is probably due to field current; the result, that is, of an electric field so strong that "some of the free electrons in the metal will be detached from the electrode and will migrate through the gas to the anode."

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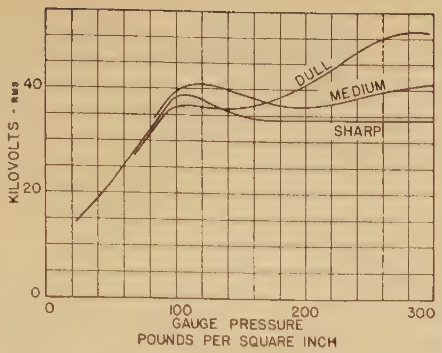

**Figure 6. Sparking voltage between points of various degrees of sharpness**

Gap: 0.30 inch

Dull: rounded tip, about 0.015 inch across
Medium: rounded tip, about 0.005 inch across
Sharp: freshly ground point, less than 0.001 inch across

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12. Breakdown of Compressed Nitrogen in a Non-Uniform Electric Field, **I. Goldman and B. Wul.** *Technical Physics of the Union of Socialist Soviet Republics*, volume 1, 1935, page 497. An abstract appears in *Science Abstracts B*, No. 2849, December 1935.

13. Breakdown of Compressed Nitrogen in Small Gaps, **I. M. Goldman.** *Comptes Rendus (Doklady) de l'Académie des Sciences de l'URSS*, volume 18, 1938, page 89. An abstract appears in *Science Abstracts B*, No. 1153, April 1938.

## Discussion

**D. W. Ver Planck** (Yale University, New Haven, Conn.): One of the important consequences of Professor Skilling's excellent paper is that it helps to establish a limit for Paschen's law. For instance in figure 5 of the paper, it can be seen that the sparking voltages for substantially uniform field begin to deviate from Paschen's law, curve *H*, at about four or five atmospheres absolute pressure.

In this connection attention should be called to the recent work of Finkelmann published in Germany (*Archiv für Elektrotechnik*, volume 31, 1937, page 282). Finkelmann working with uniform fields and about the same pressure range as Professor Skilling extended his tests to much higher spacings and voltages, and to carbon dioxide, nitrogen, and hydrogen as well as air. His results for air show that the pressure, or more correctly the density, at which deviations from Paschen's law commence increases with the gap length. Thus the limiting pressure increases gradually from Professor Skilling's five atmospheres at a gap of 0.127 centimeter to about eleven or twelve atmospheres at 0.7 centimeter. In the light of Professor Skilling's contention that the deviation is caused by removal of electrons from the cathode by direct action of the electrostatic field (so-called field current), a view also expressed by Finkelmann, it might be better to define the limit of Paschen's law in terms of the potential gradient, the quantity directly causing field current. Doing this one finds that as the gap increases from 0.1 to 0.7 centimeters, the gradient at which the deviations commence is not constant either, but increases from somewhat less than 150 to something over 300 kv maximum per centimeter.

While the data are still too few to finally establish a limiting condition for Paschen's law, its correctness for determining air density correction factors following the method recently given by the writer (AIEE Transactions, January 1938, page 45) and even for extrapolation up to pressures of several atmospheres receives further confirmation from these new researches.

It is unfortunate that Finkelmann terminated his uniform field curves too soon after the deviation from Paschen's law to show the approach to a limiting spark-over voltage at high pressure found by Professor Skilling. Finkelmann does however give results for concentric cylinders which show this phenomenon. For a gap of about 0.9 centimeter in air and a field which is only slightly nonuniform the gradient for the constant spark-over voltage is about 240 kilovolts maximum per centimeter, or only about half that observed by Professor Skilling. On the other hand, some results reported many years ago by Hayashi (*Annales de Physique*, Volume 45, number 4, 1914, page 431) for gaps quite similar in geometry to those of Professor Skilling show very much higher limiting gradients of the order of 1,000 kv maximum per centimeter. These facts are consistent with Professor Skilling's statement that various experimenters do not agree as to the heights of the level portion of the sparking voltage-pressure curves. Evidently determining factors in this phenomenon have not been brought under control.

**H. H. Skilling:** I am in thorough agreement with the discussion by Professor Ver Planck, and particularly wish to emphasize his conclusion that more data are needed. It is, of course, evident that there is room for all the work that has been done at atmospheric pressure to be repeated at many different pressure levels. The present paper is of the nature of a progress report, and it is hoped that further data can be published from time to time as they become available. The author is now extending his work to longer gaps and higher voltages.

In response to an unpublished discussion, it should be mentioned that the usual experimental procedure was to pump air into the test chamber until the pressure was somewhat in excess of 300 pounds per square inch. A valve in the supply line was then closed, and as the temperature of the enclosed air, heated by compression, approached room temperature, the pressure fell to about 300 pounds. After each measurement of sparking voltage, some of the air was released and the valve was again closed; the air was cooled by expansion, but it returned to room temperature in two or three minutes. It was not necessary to wait for room temperature to be reached before testing, as the *density* of the enclosed air could not change; the pressure gauge was read, however, after its indication had reached a steady value.

# Generator Damper Windings at Wilson Dam

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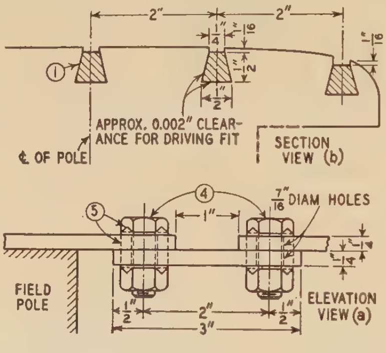
**Synopsis:** The majority of water-wheel generators now in service have been built without damper windings. Recent technical investigations and laboratory tests have indicated that, in addition to reducing oscillations and improving system stability, damper windings are very effective for reducing high-peak voltages during unbalanced short circuits. This applies particularly under switching conditions of clearing a fault when the load is disconnected from the distant end of a transmission line, and the charging current results in capacitive loading of the unfaulted phases. The existence of similar overvoltage conditions was recognized by the Wilson Dam operating staff and later confirmed by oscillograms during tests. This paper summarizes the studies and tests based on the observed overvoltage conditions and describes a method for adding damper windings to large water-wheel generators which are already installed. Short-circuit tests are extended to generators on a large scale which confirm the earlier theoretical and laboratory tests and demonstrate the advantages to be gained by adding damper windings to other water-wheel generators now in service. The tests show that damper windings in one generator when operated in parallel with another generator without dampers are effective in reducing high-peak voltages during unbalanced faults. Data are given to show the changes in machine reactances due to adding damper windings.

FOR many years amortisseur, or damper windings, were included in water-wheel generators only when they were required to meet special conditions such as high starting torque for automatic station service, synchronous condenser operation, or system-stability requirements.

The large water-wheel generators at Wilson Dam were installed during 1925 and 1926 without damper windings. The existence of an overvoltage condition during disturbances on an interconnected system was recognized by the Wilson Dam operating staff. At the suggestion of an interconnected company, overfrequency relays were installed for the purpose of disconnecting overspeeding generators although justification of this type of protection was not supported by records obtained from frequency and voltage recorders over a period of several years.



| BILL OF MATERIAL | | FOR ONE GENERATOR |
|---|---|---|
| ITEM | DESCRIPTION | NUMBER REQUIRED |
| 1 | ½" × ½" × ¼" × 50½" LONG COPPER BAR | 360 |
| 2 | ¼" × 1¼" × 12⅜" LONG COPPER BAR CUT TO FIT | 144 |
| 3 | ¼" × 1" × 3" LONG COPPER BAR | 144 |
| 4 | ⅜" × 1" HEXAGONAL-HEAD MACHINE BOLT | 288 |
| 5 | 1/32" STEEL KEEPER WASHER | 288 |

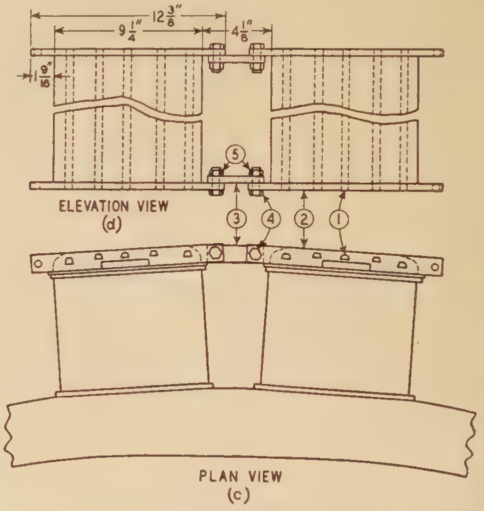


**Figure 1. Sketch showing details of damper winding installation**

(a)—Details of copper connection between adjacent poles

(b)—Section view of field pole showing location and dimensions of slots and damper bars

(c) and (d)—Plan and elevation view assembly sketches

It was expected by local plant engineers that the final explanation of this condition would be obtained during other tests with an oscillograph. During the latter part of 1935 a six-element oscillograph was purchased for use by the electrical testing laboratory. During March 1936, staged tests were made to determine certain relay and equipment characteristics. Other tests followed late in the summer. During the first series of tests one phase of a new lightning arrester broke down. This arrester failure together with the results of preliminary tests led to laboratory studies by the manufacturer and the resulting paper by Wagner.[2] The oscillograms indicated that high-peak voltages were present on the unfaulted phase during line-to-line faults on the distant end of a transmission line which had been taken out of service for tests. Peak voltages as high as 343 kv between high-voltage bus and ground were recorded on the unfaulted phase at the sending end of the 154-kv line. Peak voltages of this magnitude are severe on equipment during the duration of an unbalanced fault.

## Technical and Design Features

The generator used for these tests is rated 32,500 kva, 0.8 power factor, 12,000 volts, three-phase, 60 cycles, 100 rpm, vertical axis, and the detailed reactances are given in table III. Staged tests without damper windings were also made on a 25,000-kva generator with other data similar to the above machine except it was built by another manufacturer and similar peak voltages were obtained during these tests.

During conferences and correspondence on the subject, several suggestions were given for the prevention of damage to the equipment due to overvoltage.

1. A set of specially designed spark gaps connected between the high-voltage bus and ground and designed to operate with a few microseconds' delay after the appearance of sustained overvoltage.
2. A combination filter and protective gap connected to the generator leads.
3. The installation of damper windings which would effectively limit the magnitude of unbalanced, distorted phase potentials.

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Paper number 38-129, recommended by the AIEE committees on power generation and electrical machinery, and presented at the AIEE Southern District meeting, Miami, Fla., November 28–30, 1938. Manuscript submitted September 26, 1938; made available for preprinting November 7, 1938.

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The authors wish to acknowledge the services of the electrical testing laboratory and operating department personnel who made the tests and their assistance in analyzing the results and also the assistance of the Wilson Dam shops in working out some of the details of the winding installation.

1. For all numbered references, see list at end of paper.

4. Continue the present practice of operating the plant with all generators electrically connected to the same bus, except as required by other system operating conditions. It was also recognized that it was desirable to have other balanced loads particularly synchronous motors or condensers connected to these machines.

The first suggestion was rejected because of operating problems involved together with space requirements and cost. The transformers were already provided with protective gaps. The second suggestion was rejected for substantially the same reasons. Since the effectiveness of the first two suggestions was doubtful for this particular application and would not correct the cause, it was believed that the expense could be used to better advantage in correcting the trouble at its source. The third suggestion for the installation of damper windings was considered the most effective because the machine characteristics directly responsible for the overvoltage condition would be corrected and other benefits of damper windings for improving the stability of rotating machines would be obtained. Both generator manufacturers concurred in recommending the use of damper windings as the best solution for the machines of their own manufacture. Published information on this subject was reviewed and technical investigations were made.

Doherty and Nickle[1] stated that the voltage at short-circuit line to neutral may rise to $(2\,x_q'/x_d') - 1$ times the voltage before short circuit on the open phases. See table III for the identification of $x_q'$ and $x_d'$. This indicated that for a single-phase-to-neutral fault on the generator it was possible to obtain peak voltages 2.65 times the normal voltage across the terminals of the unfaulted phase.

The manufacturer gave some indications of improvement to be obtained by adding damper windings. These values given below represent the ratio of the peak voltage to normal voltage of the unfaulted phase during a line-to-line fault:

| Condition | Generator Only | 20 Per Cent External Reactance |
|---|---|---|
| Continuous damper | | |
| (a) maximum flux | 1.34 | 1.2 |
| (b) minimum flux | 1.17 | 1.1 |
| Discontinuous damper | | |
| (a) maximum flux | 1.84 | 1.5 |
| (b) minimum flux | 1.42 | 1.25 |

This information indicated the expected reduction in peak voltage to be obtained with each type of damper winding.

The paper by Wagner,[2] written after the designs were completed but before the last short-circuit tests, gave some useful information concerning the effect of inductive, pure resistance, induction-motor and capacity loads on the peak voltages, and the effect of damper windings. On page 1389[2] it is also stated that for a terminal-to-terminal fault on an unloaded machine, the crest of the sum of the odd harmonics measured from the sound phase to the short-circuited phases just after short circuit is equal to $(3/2)$ $(x_q'/x_d')$ times the crest of the normal line-to-neutral voltage for a machine without dampers. For a machine with damper windings the factor is $(3/2)$ $(x_q''/x_d'')$. These reactances can be identified by referring to table III of this paper. If the corresponding values for this generator are used, these formulas would indicate a ratio of 2.54 without dampers and 1.64 with the continuous damper which was added. All of the above-calculated values, unless otherwise indicated, apply to only the generator and are in fair agreement when we consider the state of knowledge of the subject and the differences in assumptions for the equations. Other factors, including the type and location of fault, different external impedances, different transmission-line constants, and the part of the reference-voltage wave at the instant the fault occurs (maximum, minimum, or some intermediate flux condition) should be taken into account, and these result in complicated computations.

During the technical investigations, additional information concerning damper windings and generator characteristics was obtained from published articles by Wagner,[3] Kilgore,[4] Wright,[5] Park and Robertson,[6] Linville,[7] and Wagner and Evans.[8] Clarke, Weygandt, and Concordia[9] have reported some additional information which was not available until our tests were completed.

Preliminary information from the manufacturer suggested the use of five round one-half-inch-diameter copper bars in each pole. This was a good theoretical shape of bar which would result in minimum change in normal field distribution at the surface of the field pole. Round bars are very difficult and expensive to install in the field on account of requiring removal of the laminations from the field pole, possible damage to the field insulation, the cost of making a new die, and requiring a punch press. Round bars can therefore be better installed at the factory.

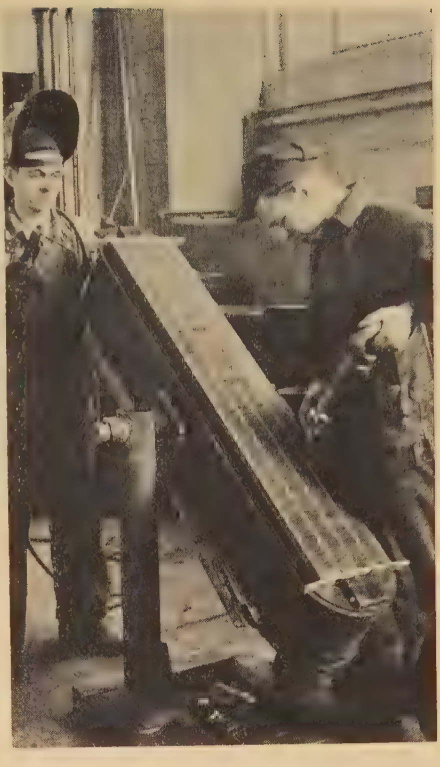
Figure 2. View showing method of swaging copper bars in slots and welding of bars to segments of short-circuiting copper rings

During the design, such items as the equipment available in the shops and in the plant, the classes of workmen available to perform each operation, features which would require dismantling the machine, if this is not desired for other maintenance work; obstructions to be avoided; available space; provision for performing each operation, such as machining, welding, etc.; mechanical re-

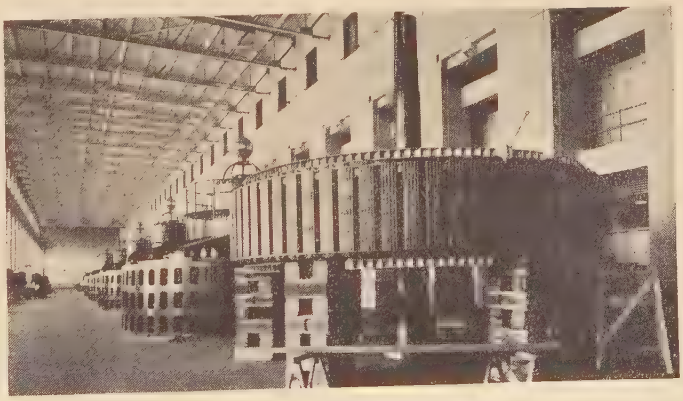
Figure 3. Rotor with field poles and bolted connections between copper segments of adjacent poles nearly completed

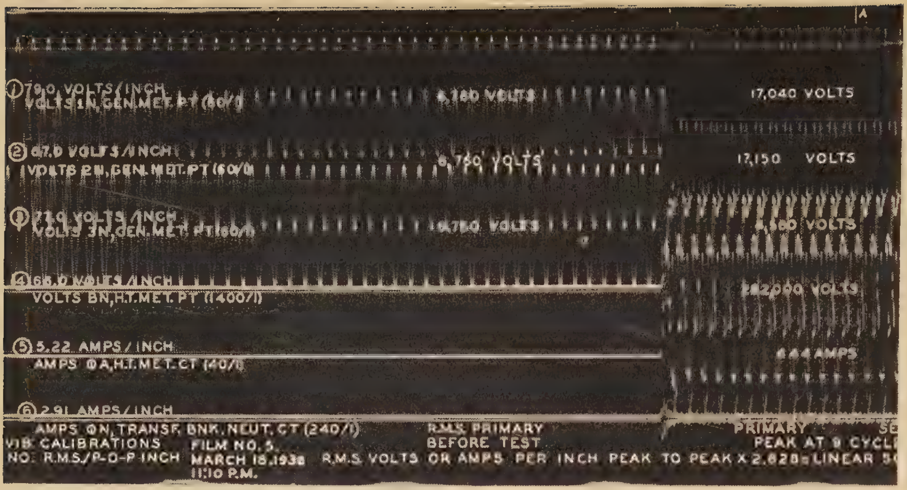

**Figure 4. Oscillogram of test number 1**

1. Generator phase-*C*-to-neutral voltage
2. Generator phase-*B*-to-neutral voltage
3. Generator phase-*A*-to-neutral voltage
4. Line phase-*B*-to-neutral voltage
5. Line phase-*A* current
6. Transformer neutral current

quirements and factor of safety during maximum overspeed; electrical, insulation, magnetic, and physical requirements, including thermal expansion, etc., had to be considered.

In order to obtain minimum disturbance to the normal magnetic field at the pole face, the one-quarter-inch minimum width of opening into the slot without excessive cost was determined by experiment in the shop. The bars were designed to have approximately the same cross section as a one-half-inch-diameter copper bar. Sketches of the preliminary design for each of the two ratings of main generators in the plant were submitted to the manufacturer of the corresponding machine for comments. The principal changes which resulted were increasing the cross section of copper links between the copper segments of adjacent poles for electrical conductivity and the use of bolted connections instead of using laminated brush copper links welded to the copper bar at each end. Slots at the bolted connection were considered a better provision for thermal expansion and contraction at this location. Sketches of the completed design for this machine are shown in figure 1.

## Details of the Damper Winding Installation

This generator had been in service approximately 12 years and the insulation was beginning to show signs of brittleness and other indications of deterioration. Special handling was therefore necessary in order to forestall serious damage to the generator parts during the course of alterations. Each field pole was carefully removed by means of a sling and placed on a truck for transportation from the powerhouse to the shops which was a distance of approximately one-quarter mile. A field pole was first mounted on the bed of a large planer in the conventional manner for cutting the slots, but difficulty was experienced in obtaining uniform slots due to the tendency of the planer tool to "dig in." The scheme selected was a modified milling head attached to the cross-feed of the planer. This equipment was designed and built for this particular application. Each of the five slots were cut in three transverses of the milling head. The angle of the cutter and the position of the planer bed holding the pole-piece was changed for each cut resulting in a slot which has the form of an inverted keystone or dovetail. The field pole was clamped securely, and during the cutting operation it was covered to prevent steel chips from dropping between the windings. The accumulation of chips was blown away by an air jet as required.

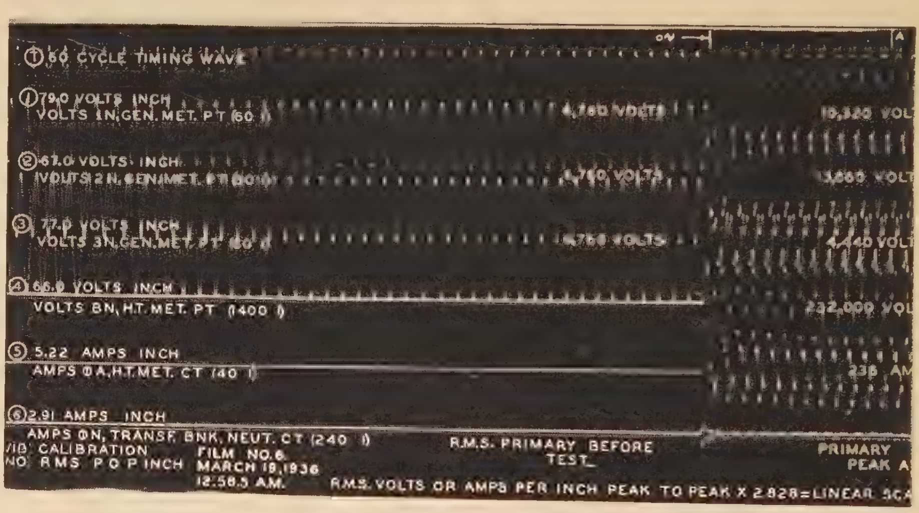

**Figure 5. Oscillogram of test number 2**

T. 60-cycle timing wave

1. Generator phase-*C*-to-neutral voltage
2. Generator phase-*B*-to-neutral voltage
3. Generator phase-*A*-to-neutral voltage
4. Line phase-*B*-to-neutral voltage
5. Line phase-*A* current
6. Transformer neutral current

The keystone-shaped copper bars were inserted in the slots. Figure 2 shows a cradle structure which was used to support the field poles and also shows how the welding and swaging were done. These operations, of course, were not performed at the same time. The electrical bonding at the ends of the bars was done by means of a carbon arc and "silphos" welding rod. Sufficient clearance was provided between the copper cross-connection and the iron laminations to allow for only differential thermal expansion and contraction. An air hammer was used in swaging the bars to make the outer part of the bars fit more firmly in the slots and prevent noise or excessive vibration while in service.

During the progress of the work, a number of tests were made to check the expansion of the bars while carrying heavy 60-cycle alternating currents. Sample welds and mechanical and electrical tests were made, as required, in order to check the suitability of the installation as well as the electrical and mechanical requirements.

Figure 3 shows the field poles nearly all assembled on the rotor. The copper bars which form the electrical connections between the damper bars of adjacent field poles may also be seen near the upper and lower part of each field pole. These bars are bolted together with steel machine bolts and steel keeper washers are used to prevent them from becoming loose. Each part of the generator was marked before dismantling and the parts were reassembled in their original locations.

The generator rotor and shaft were realigned on being put back together. All parts were cleaned and the coils were treated with insulating varnish during the course of the work. The machine when finally put back in service was in better operating condition than before this work was started.

## Short-Circuit Tests

After the generator was reassembled, short-circuit tests were made to determine the effectiveness of the damper windings. The test conditions were made to correspond with those during the tests made before the installation of damper windings.

The generator windings are connected in wye with the neutral point grounded through a resistor. The low-voltage side of the power transformer bank is connected in delta and the high-voltage side is connected in wye with the neutral solidly grounded. Potential transformers connected wye–wye to the low-voltage bus made possible the measurement of phase-to-phase, or phase-to-ground potentials. The potential transformers of the high-voltage metering equipment are normally connected open delta and these were reconnected to measure the potential between the unfaulted phase of the high-voltage bus and ground. High-voltage short-circuit currents were measured by means of wound-type current transformers located either in the high-voltage metering assembly or in the circuit between the transformer-bank neutral point and the station ground.

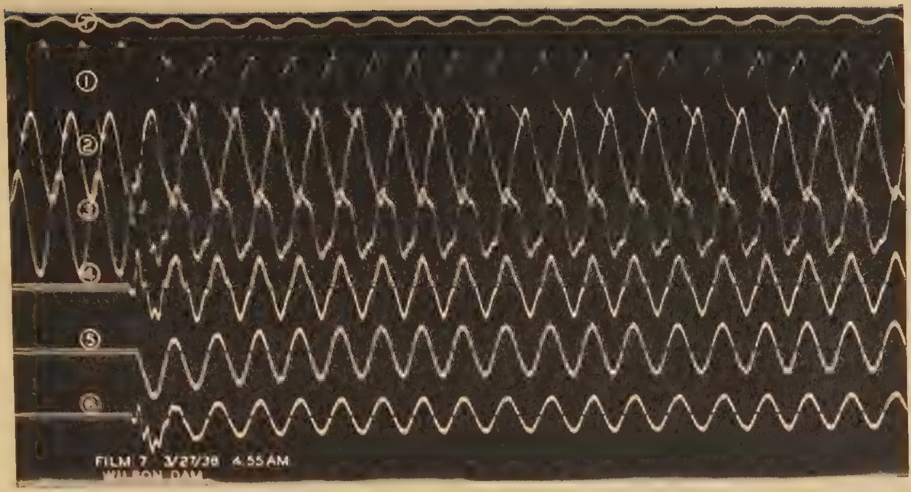

Figure 7. Oscillogram of test number 9

*T*. 60-cycle timing wave

1. Generator phase-*A*-to-neutral voltage
2. Generator phase-*C*-to-neutral voltage
3. Generator phase-*B*-to-neutral voltage
4. Line phase-*B*-to-neutral voltage
5. Line phase-*A* current
6. Transformer neutral current

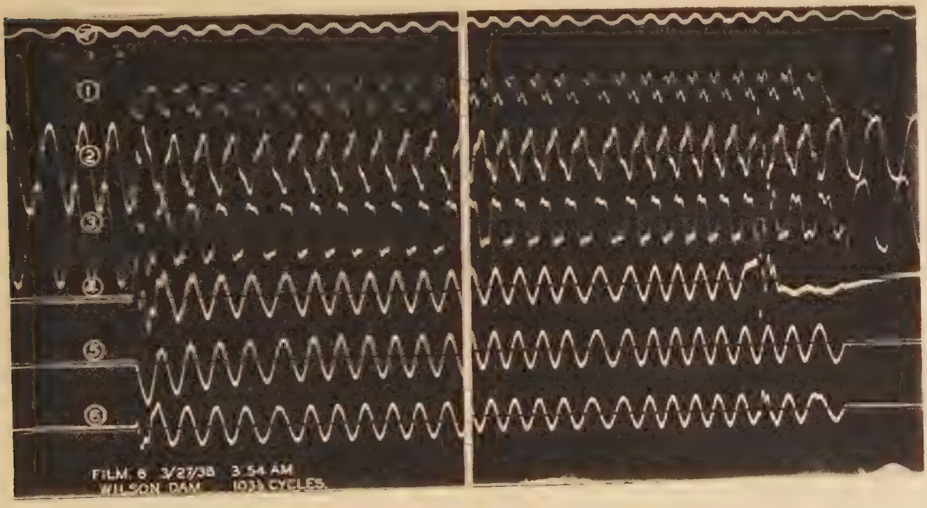

Figure 6. Oscillogram of test number 8

*T*. 60-cycle timing wave

1. Generator phase-*A*-to-neutral voltage
2. Generator phase-*C*-to-neutral voltage
3. Generator phase-*B*-to-neutral voltage
4. Line phase-*B*-to-neutral voltage
5. Line phase-*A* current
6. Transformer neutral current

Oscillograph records were made of the fault current and the unfaulted phase-to-ground potential on the high-voltage side and the three phase-to-neutral potentials of the generator. Records of field current and other features were taken during some of the tests.

All of these staged short-circuit tests were made on the Wilson Dam to Centerville section of the Wilson-West Nashville 154-kv line. This section of the line was taken out of service and fault connections were made at Centerville, Tenn., which is 68.36 miles from Wilson Dam. The generator combinations were connected to energize the transformer bank at approximately no-load voltage, and the faults were initiated by closing the high-voltage line breaker. Another high-voltage breaker and the low-voltage bus breakers were used for back-up breakers in case of emergency.

Test numbers 1 to 5, inclusive, in table I were made before damper windings were added. Test numbers 6 to 9, inclusive, were made after damper windings were added to generator number 8. During the comparison of results it was observed that tests 1 and 2 were made with 11,500 rms volts between generator terminals; tests 3, 4, and 5 were made at 11,400 volts and tests 6 to 9, inclusive, were made at 10,700 volts. In order to have all tests on the same basis for comparison, the peak voltage between the low-voltage bus and ground before the fault was applied was used as 100 per cent and compared with the corresponding voltages during the fault. The corresponding peak voltage between the high-voltage bus and ground before the fault was applied was obtained by calculation from the transformer ratio and used as 100 per cent for comparison with peak voltages existing during the tests. The transformer ratio was 10,980 volts delta to 154 kv wye. The maximum peak voltage obtained from the oscillogram after the fault was applied was expressed as a percentage of the corresponding initial peak voltage. These percentages were used as the basis for comparison.

These tests were made with no-load voltage on the generators. The fault currents and also the peak voltages during the fault would be higher if the generators had additional excitation with the generators under load. An approximate estimate of the increased voltage peaks due to additional excitation under load could be obtained by using the generator magnetization curve for the corresponding field current under load conditions and using the ratio of the new voltage to the voltages at which these tests were made. An

### Table I. Summary of Tests

| Test Number | Conditions | Phase | Low-Voltage Bus Phase to Ground Peak Volts | | High-Voltage Line Unfaulted Phase to Ground Peak Volts | | High-Voltage Line Fault Amperes at Nine Cycles (RMS)* |
|---|---|---|---|---|---|---|---|
| | | | (Kv) | (Per Cent) | (Kv) | (Per Cent) | |
| 1 | Generators 5 and 6, no reactors, bank 12, phase-*C*-to-*A* fault | *A* | 6.54 | 69.3 | | | 444 |
| | | *B* | 20.3 | 215 | 303 | 227 | |
| | | *C* | 17.84 | 189 | | | |
| 2 | Generator 6 with reactors, bank 12, phase-*C*-to-*A* fault | *A* | 5.48 | 58.3 | | | 236 |
| | | *B* | 17.25 | 183 | 303 | 227 | |
| | | *C* | 14.74 | 156 | | | |
| 3 | Generator 8, regulator in, no reactors, bank 11, phase-*B*-to-*C* fault | *A* | 20.55 | 220.5 | 343 | 261 | |
| | | *B* | 17.88 | 192.0 | | | |
| | | *C* | 5.95 | 63.8 | | | 291 |
| 4 | Generator 8, regulator in, no reactors, bank 11, phase *B*-*C*-ground fault | *A* | 13.27 | 142.2 | 196.5 | 150 | |
| | | *B* | 12.61 | 135.3 | | | |
| | | *C* | 5.95 | 63.8 | | | 251 |
| 5 | Generator 8, regulator in, no reactors, bank 11, phase-*A*-ground fault | *A* | This film | | | | |
| | | *B* | no | | | | |
| | | *C* | good | | 222.2 | 170 | |
| 6 | Generator 8, regulator in, bank 11, no reactors, phase-*A*-to-*C* fault | *A* | 5.4 | 61.8 | | | 211 |
| | | *B* | 11.5 | 131.8 | 206.2 | 166 | |
| | | *C* | 13.63 | 156 | | | |
| 7 | Generators 7 and 8, regulators in, no reactors, bank 11, phase-*A*-*C* fault | *A* | 5.09 | 58.3 | | | 325 |
| | | *B* | 14.0 | 160.3 | 231 | 186 | |
| | | *C* | 14.3 | 164 | | | |
| 8 | Generator 8, regulator in, no reactors, bank 11, phase-*A*-*C*-ground fault | *A* | 3.08 | 35.2 | | | 245 |
| | | *B* | 10.33 | 118.2 | 156.7 | 126.5 | |
| | | *C* | 13.1 | 150 | | | |
| 9 | Generator 8, regulator in, no reactors, bank 11, phase-*A*-ground fault | *A* | 8.79 | 100.5 | | | 304 |
| | | *B* | 9.14 | 104.7 | 148.7 | 119.7 | |
| | | *C* | 13.45 | 154 | | | |

* The current waves are not all perfect sine waves. These root-mean-square currents are therefore approximate.

### Table II. Comparison of Test Results

| Test Conditions | Bus | Peak Volts Without Dampers | | Peak Volts Dampers in One Generator | | Maximum Per Cent Volts Decrease With Dampers (5) | Maximum Per Cent Volts Increase Without Dampers (6) |
|---|---|---|---|---|---|---|---|
| | | Kv (1) | Per Cent (2) | Kv (3) | Per Cent (4) | | |
| Two generators Phase-phase fault | LV | 20.3 | 215 | 14.3 | 164 | 23.7 | 31 |
| | HV | 303 | 227 | 231 | 186 | 18.05 | 22 |
| One generator Phase-phase fault | LV | 20.55 | 220.5 | 13.63 | 156 | 29.2 | 41.3 |
| | HV | 343 | 261 | 206.2 | 166 | 36.4 | 57.2 |
| One generator Phase-phase-ground fault | LV | 13.27 | 142.2 | 13.1 | 150 | 5.5* | 5.2* |
| | HV | 196.5 | 150 | 156.7 | 126.5 | 15.65 | 18.6 |
| One generator Phase-ground fault | LV | Film no good | | 13.45 | 154 | | |
| | HV | 222.2 | 170 | 148.7 | 119.7 | 29.6 | 42 |

Note: Designation (LV) above refers to the maximum bus-to-ground peak voltage of the three phases of the low-voltage bus as recorded in table I, Summary of Tests.
(5)—Column (2) minus column (4), expressed as a percentage of column (2).
(6)—Column (2) minus column (4), expressed as a percentage of column (4).
* An increase in voltage at low-voltage bus is indicated, but the high-voltage line shows a reduction.

exact solution would require detailed calculations involving the internal characteristics of the generator.

Figures 4 to 7, inclusive, are oscillograms of test numbers 1, 2, 8, and 9, respectively. The voltage and current values printed on the films of figures 4 and 5 are the magnitudes at nine cycles made during preliminary analyses. The maximum peak voltages used for the comparison of test results are given in table I.

Table I shows the station combinations used for each test, the type of fault, and the resulting peak voltages and per-cent voltages. Generators 5, 6, 7, and 8 are identical machines and the transformer banks are identical.

Table II is a comparison of test results before and after damper windings were added to generator number 8. This table also shows the per-cent increase in peak volts which were obtained before this type of damper winding was added to the generator. The advantages to be gained by adding damper windings to water-wheel generators now in service are self-evident.

Theoretical calculations were not made to determine if a different length of transmission line would result in higher peak voltages. C. F. Wagner[2] has reported that transmission lines having different lengths or different constants will produce harmonics of different magnitude and therefore different peak voltages during unbalanced faults without damper windings in the generator.

## Changes in Generator Reactances

Table III gives the calculated per unit reactances of the generator without damper windings and the corresponding values after damper windings were added. These calculated reactances were obtained from the manufacturer.

## Conclusions

1. The results obtained in the reduction of peak voltages for different types of unbalanced faults are summarized in table II. These percentages may change a slight amount if the faults occurred at different points of the voltage wave of the short-circuited phase, but these tests may be considered as representative of the improvements to be expected.

2. These tests show that one generator with damper windings when operated in parallel with another generator without damper windings is very effective for reducing the peak voltages during unbalanced faults.

3. A close inspection of the open-circuit voltage of the oscillograms in figures 6 and 7 will reveal five very small voltage ripples corresponding to the five damper bars in each pole. These voltage ripples, or harmonics, are too feeble to cause telephone interference and they are not noticeable when the machine is operated in parallel with another generator. These harmonics can be reduced by using round copper bars or reducing the width of the dovetail-shaped copper bars near the surface of the field poles, but it would be more expensive and would result in a more difficult mechanical job of machining the slots for the damper bar installation.

4. Since the direct axis subtransient, negative-sequence, and zero-sequence reactances have been reduced, the fault currents are increased by the addition of damper windings. However, for faults beyond the generator bus the external impedance prevents the fault current from being increased in direct proportion to the reduction in generator reactance. Table I shows the comparative root-mean-square fault currents in the high-voltage line nine cycles after the beginning of the fault.

5. It is believed that the installation of damper windings will solve some of the problems of operating companies who have unexplained voltage surges during system disturbances.

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### Table III

| Per Unit Reactance | | Amortisseur | | Per Cent Reduction |
|---|---|---|---|---|
| | | Without | With | |
| Leakage | $x$ | 0.22 | 0.22 | 0 |
| Direct synchronous | $x_d$ | 1.15 | 1.15 | 0 |
| Quadrature synchronous | $x_q$ | 0.73 | 0.73 | 0 |
| Direct transient | $x_d'$ | 0.40 | 0.40 | 0 |
| Quadrature transient | $x_q'$ | 0.73 | 0.73 | 0 |
| Direct subtransient | $x_d''$ | 0.32 | 0.265 | 17.2 |
| Quadrature subtransient | $x_q''$ | 0.73 | 0.29 | 60.3 |
| Negative sequence | $x_2$ | 0.48 | 0.28 | 41.7 |
| Zero sequence | $x_0$ | 0.14 | 0.123 | 12.13 |

2. UNSYMMETRICAL SHORT-CIRCUITS ON WATER-WHEEL GENERATORS UNDER CAPACITIVE LOADING, C. F. Wagner. ELECTRICAL ENGINEERING, November 1937, pages 1385–95.

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## Discussion

**H. E. Bussey** (General Electric Company, Atlanta, Ga.): The authors of this paper present in an admirable manner the advantages to be derived by the addition of amortisseur windings to salient-pole generators in the suppression of overvoltages occasioned by short circuits. Great ingenuity is shown in coping with the mechanical problems incident to the installation of amortisseur windings in a generator as large as this, not originally designed for amortisseur windings, and with limited mechanical facilities.

Much has been written on this subject as may be seen from the bibliography accompanying the paper, but only in the last few years has any great weight been given to the importance of amortisseur windings on salient-pole generators in the suppression of high voltages under short-circuit conditions.

The present paper is an important contribution in that it presents the field experience before and after the application of amortisseur windings, so that a direct comparison can be drawn as to the effectiveness of the addition.

The authors mentioned in the bibliography accompanying the paper the work of Clarke, Weygandt, and Concordia as represented by AIEE paper No. 37-74. In this paper some very important considerations are set forth and while the paper by Clarke, Weygandt, and Concordia is now of common knowledge, a statement of the conclusions of this paper may not be out of order in this discussion. It is stated that the principal determining factor for the magnitude of overvoltages caused by line-to-line short circuits is the ratio $x_q''/x_d''$, of quadrature-axis subtransient reactance to direct-axis subtransient reactance, and that this ratio is a function of the amortisseur characteristic.

The maximum possible overvoltage caused by a line-to-line short circuit on an open-circuited machine is given very closely by the formula

$$e_{max} = 2\frac{x_q''}{x_d''} - 1$$

An important point is that the overvoltage may be considerably increased over the value of this equation by terminal capacitance, the worst condition arising when the capacitive reactance is equal to nine times the negative-sequence reactance of the generator.

In the design of an amortisseur winding for salient-pole generators, consideration must be given not only to the design constants of the generator and to the characteristics of the transmission line and the load, but should also take into account the effect of the design of the amortisseur winding on the reactances of the machine.

For the reasons pointed out, it is desirable that where amortisseur windings are to be applied to existing machines that the manufacturer be freely consulted as much valuable data on the design constants of the generators in question is available from this source. Manufacturers will, I am sure, be glad to co-operate on existing machines not having amortisseur windings.

**S. B. Crary** (General Electric Company, Schenectady, N. Y.): This paper is of considerable interest as it shows the results of tests made on the same machine under similar conditions before and after an amortisseur winding was installed. Such a direct comparison is not always possible. These tests indicate the improvement that may be realized by the use of an amortisseur winding, and are in general agreement with the mathematical analyses which have recently been made of this phenomena.

Whether or not to install amortisseur windings in water-wheel generators has been the subject of discussion for a number of years. It has been realized that they are generally beneficial. However, these benefits did not always seem to be sufficiently important to justify the additional expense of their installation. As a result, as stated by the authors, there are many water-wheel generators which do not have amortisseur windings. It seems to be in order briefly to review benefits which are now recognized as being obtained by their use in water-wheel generators.

1. Amortisseur windings are of value in providing additional torque for generators which are automatically synchronized when such synchronization may occur when the machine is out of phase or slightly off system speed, and also in increasing the possibility of pulling back into synchronism in case synchronism is lost following a system disturbance. The amortisseur windings give additional torque besides that provided by the main field winding, which may be quite limited except at a slip very close to synchronous speed even when the discharge resistance is in the circuit, because of the inadvisability of using a high value of discharge resistance.

2. Amortisseur windings reduce hunting which may become a definite problem under certain circuit conditions as they provide positive damping when a machine is operating at light load. This is of particular value when it is desired to operate a water-wheel generator as a synchronous condenser or under the condition of overexcitation with small kilowatt load. The tendency for oscillation is increased when the machine is connected by lines having an appreciable amount of resistance to the power system or load.

3. Amortisseur windings, because of their tendency to damp out the oscillations more quickly, are of some benefit in improving the ability of machines to ride through system disturbances, faults, and switching operations. This gain in stability, however, is small. High-resistance amortisseur windings or a double amortisseur winding having low- and high-resistance windings were at one time proposed. The advantage of the high-resistance winding is that it provides a braking torque during the period in which an unbalanced short circuit is on the system. This torque, to the extent that it loads the generator, is of benefit in increasing the stability limits. However, with quick switching and the need for systems to ride through the more severe three-phase faults, the benefits of a high-resistance winding do not seem to justify the expense of its installation.

4. Amortisseur windings are effective in reducing circuit-breaker recovery-voltage rates. Messrs. Park and Skeats have shown that the rate of rise is a function of the ratio $x_q''/x_d''$.

5. Amortisseur windings are also of benefit in protecting the field winding against current surges in the armature circuit which may be caused by lightning or internal short circuits. The amortisseur winding reduces the induced voltage in the individual field-pole windings and is a factor under these conditions in reducing the field circuit insulation stress.

6. Amortisseur windings are effective in reducing the overvoltages due to unbalanced faults as has been shown recently by two papers, which have analyzed this phenomena, and by the paper under discussion, which has indicated by test the improvement which may be obtained by the use of amortisseur windings.

The reduction of overvoltages due to unbalanced faults is another reason previously not fully recognized why an amortissuer winding should be used in a water-wheel generator. With the effort to co-ordinate insulation levels and provide proper protection for system equipment, the use of a properly designed amortisseur winding is a step in a direction which will allow further economies and improvements to be made. It now appears that with a fuller recognition of these advantages amortisseur windings will be used more in the future than they have been recently.

We believe that it would be very interesting and worth while if the authors could give information as to the ratio of the quadrature to the direct axis reactances before and after installation of the amortisseur windings. If static tests for the $x_q''$ and $x_d''$ could be made, this would be an indication of the effectiveness of the amortisseur windings at Wilson Dam, as the ratio of these reactances is a fair measure of the ability of the amortisseur to reduce the overvoltages. In checking over the data given in the paper, apparently the reactance of the transformer banks (11 and 12) used in the tests was not given. This would be of interest if it were desired to make calculations to check the magnitude of overvoltage obtained in the tests.

**R. B. George:** I wish to acknowledge the fine co-operation we received from the manufacturers during this work, particularly in furnishing generator reactance data and in giving constructive criticism of the proposed design before we started the work of installing the damper windings.

Mr. Bussey's statement concerning how much has been written on this subject is true at the present time, but the most useful contributions for future undertakings were published after our designs were completed. Wagner's paper[2] and Clarke, Weygandt, and Concordia's paper[9] were published after our design was completed. Mr. Wagner also published a series of articles on this subject in the *Electric Journal* during 1938. When my theoretical studies were made, the paper by Doherty and Nickle[1] and Wagner's paper[3] were the only ones I found directly applicable to the problem. Some useful information is contained in references 4 to 8, inclusive, of the bibliography but, since these papers cover different subjects or viewpoints, one should be well acquainted with the technical features of the problem to apply them to this problem.

Mr. Crary's discussion gives a good summary of the uses of damper windings and the benefits to be obtained by installing them.

For the generator without damper windings, the ratio $x_q'/x_d' = 1.825$. After damper windings are added, we use the ratio $x_q''/x_d''$ which is equal to 1.132. Since the ratio of the quadrature-axis reactance to the corresponding direct-axis reactance is a measure of the peak voltage during unbalanced faults, a reduction of 37.97 per cent is indicated. The calculated values of quadrature-axis and direct-axis reactances are given in table III of the paper. No tests were made to measure the various reactances because such tests are expensive and some of them would require precautions to prevent injury to the windings of a generator which had been in operation for nearly 12 years.

The transformer banks were identical and have 0.221 per cent resistance and 9.88 per cent reactance at 65,000 kva base. The constants of the transmission line are 23.4 ohms resistance, 53 ohms reactance, $349 \times 10^6$ mhos total susceptance, length 67 miles, and operating voltage 154 kv.

If studies of combinations of generator, transformer, and lines are made, the inductance corresponding to the negative-sequence reactance should be used at the harmonic frequency being studied. Formulas for various features or combinations may be found in references 1, 2, and 9 of the bibliography.

# Reconditioning of Insulating Oils by Activated Alumina

By J. E. HOUSLEY
ASSOCIATE AIEE

THE use of insulating oil in electrical equipment carries with it the problem of prevention of deterioration when the oil is subjected to elevated temperatures in the presence of air. Deterioration may be accelerated by the presence of moisture and organic acid. This condition is found in certain types of transformers and oil-filled bushings.

Since oxidation of oil results in an increased acidity which can be determined by tests, it is possible to gauge the rate of deterioration by making tests at intervals. The degree of deterioration is determined by the weight in milligrams of potassium hydroxide required to neutralize the acidity of one gram of oil. This test has been described by the American Society for Testing Materials as a "Tentative Method of Test for Neutralization Number for Petroleum Products and Lubricants," designation: *D*-188-27-*T*. The neutralization number so obtained is the weight in milligrams of potassium hydroxide to neutralize one gram of oil.

## Effects of Oxidation

After oil has reached a relatively high acidity number the products of oxidation appear as a sludge in the oil. A pasty coating forms over all parts of the equipment which are immersed in oil. The deposit is greater in thickness where there is a marked differential in temperatures between the oil and the immersed surface. The increase in the thickness of the deposit is especially noticeable on water cooling coils. In the case of transformers, the removal of heat from the core to the heat-radiating surface is retarded and the transformer operates at an increasingly higher temperature under a given load condition. In time the transformer must be removed from service and the sludge washed from the core with a high-pressure stream of oil, and the sludge must be removed from the cooling coils or other radiating surfaces.

In oil-filled bushings a number of factors affect the formation of acid and sludge. Means are usually taken to shield the oil in the gauge glass from sunlight by the use of paint or amber glass. Contact of circulating oil with air should be avoided. Heat from sunlight with a higher ambient temperature on transformer locations indicate that transformer bushing oil should have a higher rate of acid formation. The neutralization number obtained by testing the oil in a large number of 150-kv bushings indicated that sludge formation would start in about four years where the bushings were located on transformers, and in about five years where the bushings were located on oil circuit breakers. After the neutralization number reached 0.5, considerable difficulty was experienced in cleaning the bushings free of sludge. Where the bushings were not equipped with a device to prevent the entrance of moisture, a considerable amount of water was found in the oil. Some bushings are now equipped with a device to prevent the entrance of moisture and at the same time circulation of the oil in the body of the bushing does not bring it in contact with the air surface. The principle of the conservator type of transformer is used in this device.

## Control of Oxidation

In recent years the rate of oxidation has been brought under control by the use of two methods in new transformers. One method is the use of the conservator type of transformer, and the other method involves the introduction of nitrogen in the place of air above the surface of the oil.

In several large industrial plants the problem of maintenance of electrical insulating oil in old transformers became acute. About 500,000 kva capacity in both high- and low-voltage transformers were involved in the problem. In 1932 experiments were started with the use of activated alumina both as a desiccating agent and acid adsorption agent in the control of oxidation of oils in steam and

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The development work described in this paper was carried on by the author who acknowledges the valuable contributions of time and ideas by O. H. Pierce.

hydraulic turbines, transformers, and bushings.

## Qualities of Material

Activated alumina is a relatively new type of solid adsorbent and it has been employed as a desiccant for dehydration of gases, vapors, and liquids. In the treatment of oils its selective adsorptive property was found to be very effective for the removal of acid in solution. The method which has proved satisfactory is to contact the oil with activated alumina, after the oil has been treated in a centrifuge or a blotter-paper press to remove the sludge and moisture. A sufficient time-interval contact with the activated alumina is necessary to allow adsorption through the highly porous granules. The material is essentially aluminum oxide, in porous form. It is classed among the commercially pure chemicals. For oil treatment the best results were obtained with grade-A activated alumina in granular form, crushed to 4–8 mesh size. The granules have high strength and resistance to crushing, shock, and abrasion and, therefore, tend to retain their original size and produce a minimum of dust during use. The weight of the packed material is approximately 50 pounds per cubic foot. The size of particles was selected to give a satisfactorily low resistance to flow of oil through the filter bed. The most important problem in developing the material for the maintenance of oil was the reactivation of the material after it had reached its adsorptive capacity. This placed the material on an economic parity with fuller's earth.

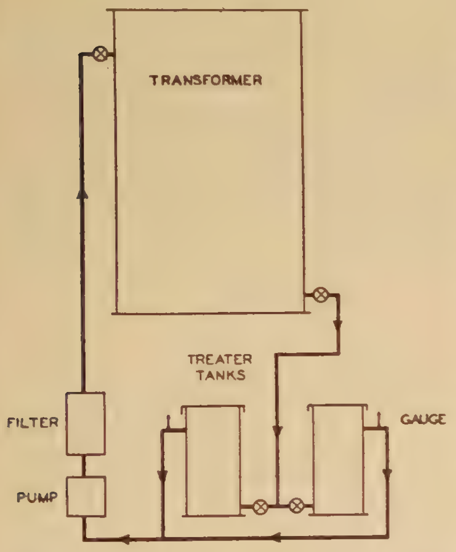

**Figure 1. Schematic diagram of oil treating equipment using open-type tanks**

Certain advantages and economies accrue to the operating engineer in having a single material which will cover the usual problems encountered in the maintenance of oil. The major requirements may be stated as follows: The removal of moisture and the removal of acidity as formed in the oil contained in oil-filled bushings. The removal of acidity from deteriorated oil. The removal of acidity from reconditioned or new oil by automatic external apparatus or by direct immersion in oil storage tanks or in certain small oil-filled apparatus.

## Method of Use

In large transformers which could not be removed from service for an extended period, the following method of removal of acidity was used. All sludge was removed from the tank and core of the transformer as well as from the oil. After returning the transformer to service, the oil was circulated through a blotter-paper press into a tank filled with activated alumina and thence through an automobile-type filter into the transformer. The tank should be of a closed type if the pump on the filter is used to force the oil through the activated alumina into the transformer. Sludge-free oil may be caused to flow by gravity through the activated alumina into the blotter-paper filter press and pumped directly into the transformer. In this case the tank containing the adsorbent need not be a closed vessel. The oil should be admitted at the bottom and flow upward in order to carry a minimum of dust, although the amount of dust is very small. The open-type tanks used consisted of discarded lightning-arrester tanks. In treating 12 7,000-kva transformers, 150/13.2-kv rating, 1,600 pounds of activated alumina was used, half of the quantity being placed in each tank. Each transformer contained 3,300 gallons of oil. Figure 1 shows a diagram of the arrangement of the equipment, using open tanks. Figure 2 is a photograph of the open-type tanks.

**Figure 2. Open-type oil treating tanks**

## Quantity of Material

The quantity of activated alumina required for a given amount of oil is based on the condition of the oil and the final neutralization number desired. This may be determined by reference to figure 3. In the foregoing example, the oil had a neutralization number of 0.70. A final neutralization number of 0.10 was desired. The approximate weight of one gallon of oil is $7^1/_2$ pounds. The weight of 3,300 gallons of oil is 24,750 pounds. Referring to the chart, figure 3, the initial acidity of 0.70 is found and traced vertically to the intersection with the curve marked 0.10 as final acidity and to the

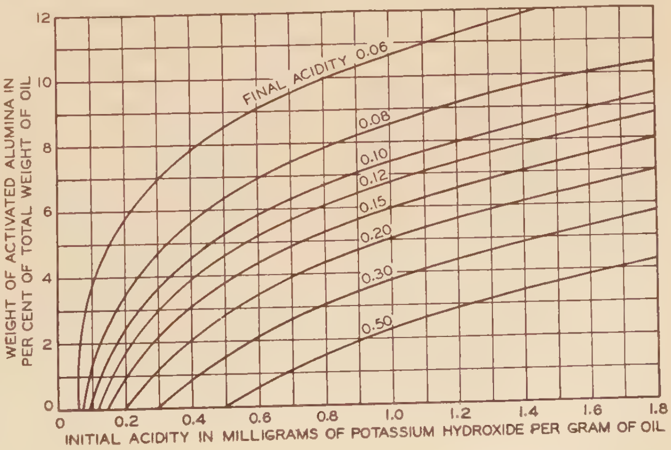

**Figure 3. Chart showing quantity of activated alumina required for oil treatment**

left horizontally where the weight of activated alumina will be found to be 6.3 per cent of the total weight of the oil. Therefore, 1,559 pounds will be required to treat the specified 3,300 gallons of oil. About 60 gallons of oil remained in the activated alumina and was lost during each reactivation.

### Time Required

The length of time required for the correction of acidity varies according to certain conditions. The higher the acidity the faster the correction for a given amount of material. The longer the material is used, between reactivations, the slower becomes the rate of adsorption. It is economical to reactivate the material before reaching the end point. There is a slight slowing up in efficiency of the process on account of low temperatures.

The minimum size of transformer treated was 100 kva. In small transformers the best method is to suspend a canvas bag, filled with activated alumina, inside the transformer. If this is not desirable, the oil may be accumulated and treated in a quiescent state for ten days in a tank containing about one-tenth pound of activated alumina for each pound of oil.

The tank may be refilled with oil several times before reaching the capacity of the adsorbent. The maximum time required for treatment of one transformer was eight weeks for a 14,000-kva transformer containing 4,000 gallons of oil. One operator was used, working 40 hours per week, 2,100 pounds of activated alumina were used. (The acidity at the beginning was at neutralization number 0.98 and 0.14 at the end.)

In the treatment of 12 7,000-kva transformers of the type described in the preceding paragraph, one operator worked 40 hours each week for six weeks on each transformer. The oil was circulated at a rate of 7,000 gallons per week or 175 gallons per hour. Rapid circulation does not give a sufficient time for the oil to remain in contact with the material. The acidity was reduced from a neutralization number of 0.70 to 0.10. The rate of correction by weeks follows:

| | |
|---|---|
| First week | 0.70 to 0.46 |
| Second week | 0.46 to 0.34 |
| Third week | 0.34 to 0.22 |
| Fourth week | 0.22 to 0.17 |
| Fifth week | 0.17 to 0.12 |
| Sixth week | 0.12 to 0.10 |

The material was reactivated at the end of the second and fourth weeks in order to gain a slight increase in rate of correction.

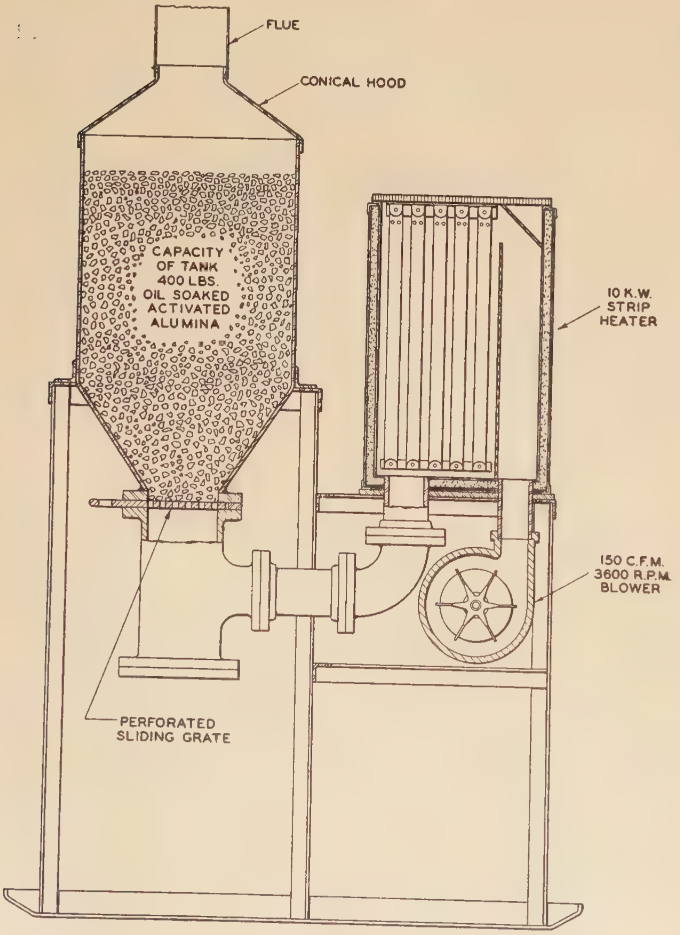
FLUE
CONICAL HOOD
CAPACITY OF TANK 400 LBS. OIL SOAKED ACTIVATED ALUMINA
10 K.W. STRIP HEATER
150 C.F.M. 3600 R.P.M. BLOWER
PERFORATED SLIDING GRATE

**Figure 4. Reactivating unit**

During the reactivation process, one tank containing 750 pounds of material would be taken out of service with the other tank maintained in operation. After the process slows up, experience indicates that the final reduction may be made automatic by the means of using a thermo-syphon by-pass filter. By the use of the proper quantity of material the acidity may be further reduced or an equally satisfactory condition is to maintain the oil at a reasonably satisfactory level which is believed to be anywhere below a neutralization number of 0.20. In the job described the process was continued two weeks longer than usual because the transformers were being fitted with inert-gas equipment and the automatic equipment was not considered necessary.

### Reactivation Process

It has been indicated that there is a definite limit to the amount of acidity which may be adsorbed by the material. After this point is reached, the activated alumina may be reactivated. This also means that a smaller amount of material may be used by stopping the operation and reactivating the adsorbent as many times as necessary. No limit has been found in the number of times reactivation may be made, but the mechanical wear during handling will cause a loss of about 3 per cent during each reactivation.

The reactivation process consists of heating the oil-soaked activated alumina, in a suitable container, with hot air at 400 degrees Fahrenheit blown through the bed of alumina. When the temperature of the bed exceeds the ignition temperature of the oil, combustion proceeds with air supplied at room temperature until all carbonaceous material is consumed. Control of the draft should be used so that the temperature of the activated alumina does not exceed 1,000 degrees Fahrenheit. Temperatures in excess of 600 degrees Fahrenheit permanently impair the activated alumina for the adsorption of moisture, but do not affect its property of adsorption of acid from oil

### Reactivation Unit

A diagram of the reactivating unit is shown in figure 4. A 3,600-rpm two-inch blower, driven by a one-fourth-horsepower motor delivers 150 cubic feet of air per minute to the heating chamber which contains 10 kw in electric space heaters. A four-inch pipe conducts the air, heated to 400 degrees Fahrenheit, to the base of the tank containing 400 pounds of activated alumina. The opening of the coni-

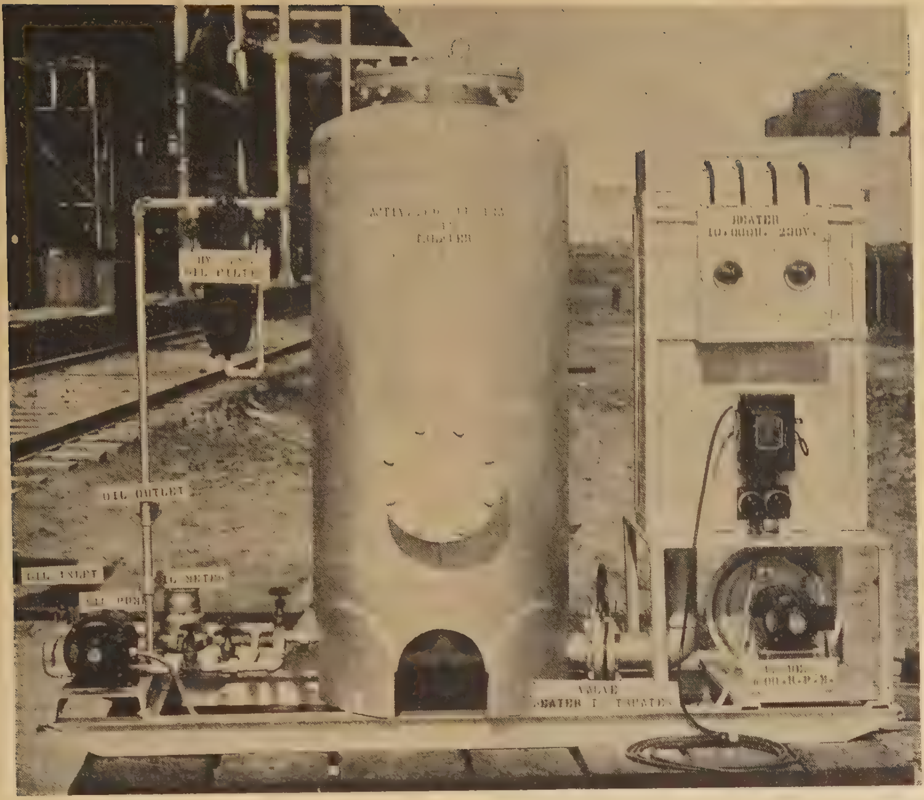

Figure 5. Reactivating unit

cal base is covered with a cast-iron sliding door, perforated to admit the air blast. The tee-fitting is attached to the base of the container and a blank cover is bolted on. This cover is removed and the sliding door or grate above is removed in order to remove the material after reactivation. Figure 5 is a photograph of the combined reactivating and oil treating unit.

## Care of Oil

Consideration has been given to oil which had reached an advanced stage of deterioration. After an oil has been cleaned and the reduction of acidity accomplished, or in the case of new oil, it is desirable to maintain the oil well below the sludging point. In order to do this the transformers have been equipped with a small external tank filled with activated alumina in six-ounce canvas bags. In one group of 14 2,500-kva transformers, the external tank was made from a four-foot section of 10-inch pipe, fitted with flanges at top and bottom. A one-inch diameter pipe connects from the top of this tank to the oil filling connection at the top of the transformer. A similar pipe connects the bottom of this tank to the drain connection on the transformer. The difference of temperature between the top and bottom of the transformer provides a circulation of the oil by thermo-syphon effect. The external tank was charged with 50 pounds of activated alumina which will maintain the 700 gallons of oil contained in the transformer at the original acidity for one year. These transformers are operated at a slight overload continuously and past experience indicates that the neutralization number increases about 0.20 in one year. With a known rate of deterioration and a given quantity of oil, the size of the by-pass unit may be determined for any desired time interval by reference to chart, figure 3. Figure 6 shows a thermo-syphon treater mounted on each of three 333-kva, 13,000/440-volt transformers.

## Oxidation of Treated Oil

Experience with transformers operating with treated oil, dating from 1932 to the present, indicates that none of the old types of oil as well as the new types of oil show an increase in acidity at a faster rate after having the acidity lowered by this treatment. This examination included transformers ranging from 100 kva to 14,000 kva.

## Bushing Oil

More than 75 150-kv bushings have been equipped with a small bag, made of heavy cotton cloth, known as domestic, filled with three pounds of activated alumina. This bag is coiled in the form of a horseshoe in the glass bowl at the top of the bushing. This is the maximum quantity which could be placed in the space available. Experience checks the calculation that this amount of material should keep the oil in original condition for two years. The bags are changed during the regular inspection periods. The use of new material permits the use of water adsorption, in addition to acid adsorption. Experience indicated that all of the water which entered by breather action was adsorbed by the material.

## Transformer Breather

Another serious contamination of transformer oil results from the entrance of water into transformers through the normal breather action caused by changes in temperature. The prevention of entrance of moisture has been studied as a parallel problem to the one of preventing

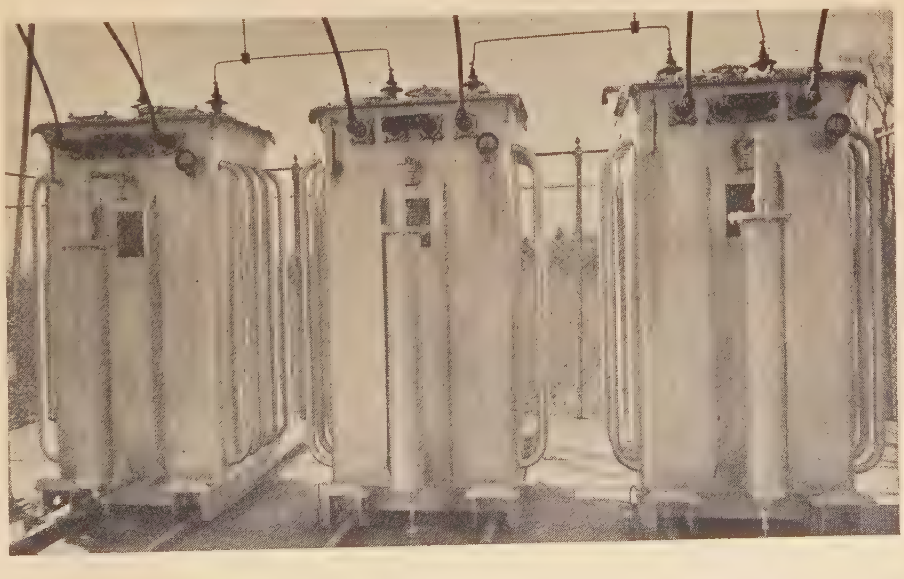

Figure 6. Thermo-syphon treaters

the ill effects of oxidation. A very practical type of dehydrator was developed with a sight indicator showing the condition of the desiccator in relation to exhaustion of adsorption properties. The design is shown in figure 7, and a photograph of one installation is shown in figure 8. In this installation, the material used was 20 pounds of grade *E*, 8–14 mesh, activated alumina, which is colored by a chemical which is blue when the material is in the dry state. As moisture is adsorbed it gradually fades to a light pink when completely saturated. The physical state of the material does not otherwise change. The material may be reactivated, unless accidentally oil-soaked, by heating in a ventilated electric oven to a temperature of 350 to 600 degrees Fahrenheit until the blue color is restored.

The first transformers to be equipped were five 4,000-kva oil-insulated self-cooled units. At the time of installation, the dielectric test of the oil averaged 22,400 volts. Three months later the average test was 28,800 volts. These transformers previously required filtration of the oil to remove moisture every 12 months.

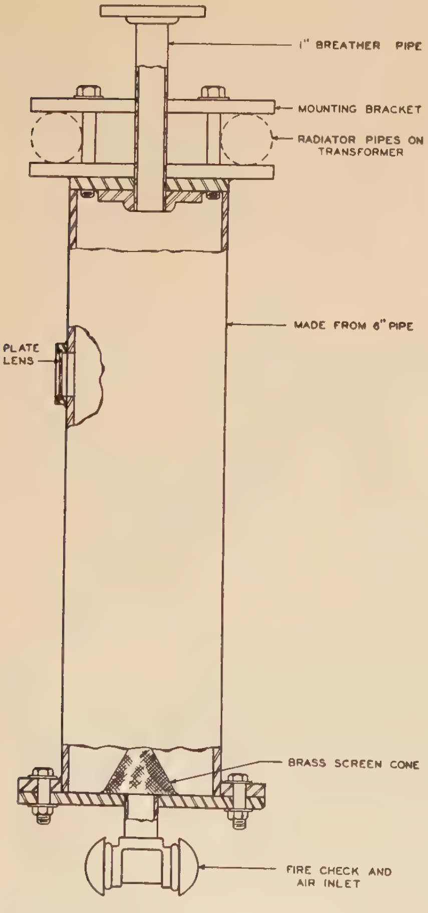

Figure 7. Transformer breather using activated alumina

## Conclusion

The development of the apparatus and methods for the maintenance of oils has given the industry a new approach to a difficult problem which concerns the continuity of service of power equipment. Other materials which have long been available were restricted to use in central storage and treating plants. Such use is restricted to treatment after considerable deterioration has taken place. A program of preventive maintenance led to the development of apparatus and the selection of a material which would remove acidity as formed in field apparatus. The problem was not considered solved until methods, apparatus, and material were adapted to portable use in any field location. One operator of a semi-skilled type is required only during the initial reconditioning process and the infrequent reactivation of material in automatic filters.

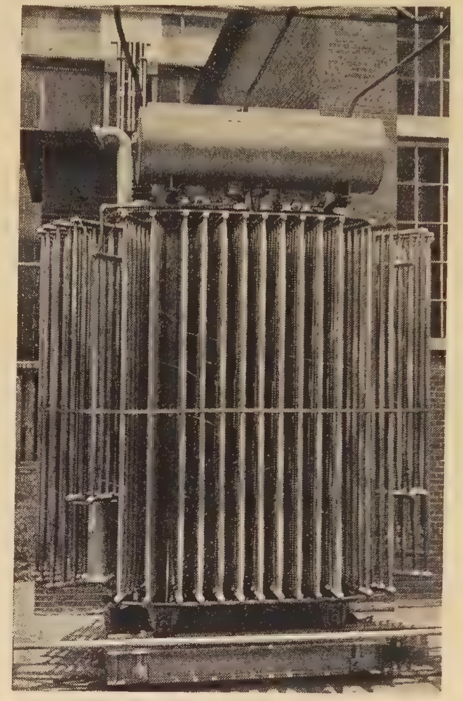

Figure 8. Transformer breather

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## Discussion

**J. H. Battle** (Memphis Power and Light Company, Memphis, Tenn.): Mr. Housley's paper pertaining to the maintenance of insulating oil is very timely. There is a definite need today for some means of reducing the acidity of insulating oil. Speaking from the power companies' point of view, loads are increasing to the full-load point and even above on equipment that has been in service eight or ten years or longer. The oil in this equipment tends to sludge easily and is difficult to maintain at a reasonable dielectric strength. The sludging causes decreased heat dissipation efficiency. The difficulty in maintaining reasonable dielectric strength causes additional maintenance expense.

As the author points out various means have been devised to slow up the deterioration process. These means may take the form of: reducing the area of oil exposed to the air; keeping moisture, a source of oxygen, out of the oil; or keeping an inert atmosphere above the oil by eliminating the oxygen in the air.

Reducing the area of the oil exposed to the air is accomplished by use of a conservator or expansion tank. Since the oil in the conservator tank gets as hot as the transformer and since on the older transformers this conservator tank is open to the air, the oil in the conservator tank becomes deteriorated. The alternate heating and cooling of the transformer breathes this deteriorated oil into the transformer tank. About a year and a half ago we installed magnetic oil gauges in the conservator tanks of about 19 large power transformers. In all of these conservator tanks we found very bad sludge conditions. Any method to protect the oil in the conservator tank will further protect the oil in the transformer tank. The dehumidifier breather the author describes in his paper will prevent moisture from entering the conservator tank. Thus it will slow up the deterioration process. A more desirable breather would be one that would eliminate the oxygen also.

To us the problem of maintaining in good condition the oil in large conservator-equipped power transformers is not so acute as another problem. That problem is the maintenance of oil in underground distribution transformers. On the Memphis Power and Light Company system the single-phase units range in size from 50 to 150 kva. The three-phase units are 300 kva. Thus each unit contains only a small amount of oil relative to a power transformer but the total of our whole underground system amounts to about 25,000 gallons.

We have found that the dielectric strength of about half this oil becomes unsatisfactory in a year's time. So each spring rather than make dielectric tests on each bank of transformers, we change the oil in the whole underground system. The change is done by means of an electric tank truck. The old oil is pumped out of the transformer, the core and coils flushed off, and reconditioned oil pumped back in. From 1,200 to 1,500 gallons is changed per day.

The old oil is reconditioned by means of a combination centrifuge and blotter press. We have frequently had trouble bringing this oil up to a satisfactory dielectric strength. Sometimes we have found it necessary to run one batch through the machine several times. Acidity tests show that this oil is high in acid. With the end in view of reducing the acidity of this oil, we have experimented with activated alumina. Our outfit consists of two 300-gallon oil tanks equipped with immersion heaters and an alumina tank made from an old water tank 13 inches in diameter and 58 inches high. The tanks are piped so that oil may be transferred from tank to tank through the alumina or circulated through the alumina from one tank. The temperature of the oil is maintained at about 130 degrees Fahrenheit and is pumped through the alumina at a rate of about 60 gallons an hour. The alumina tank contains about 225 pounds of the chemical. We have found that the alumina does reduce the acidity but it is slow. Our experience is that it takes eight to ten hours to reduce the acidity by $^1/_{10}$ milligram KOH per gram of oil when the acidity is high and longer when the acidity is low. Of course, we could speed up the process by using more alumina but this would increase the cost.

Where it is desired to absorb the acid as it is formed in the oil, alumina answers the purpose very well. The alumina may be placed in bags inside the transformer, oil switch, or storage tanks. The author's method of using an external tank connected to valves at the bottom and top is preferable in the case of transformers in that it does not interfere with the circulation of oil within the transformer.

In the reactivation process it is very desirable that the alumina be handled as little as possible in order to cut down waste and save labor. The best method would be to reactivate the alumina in the same tank the oil is reconditioned in. We would like to ask the author what his experience on this has been.

In conclusion may we repeat that there is a definite need for some method of reducing the acidity of deteriorated insulating oil and Mr. Housley's methods seem to be an answer.

**Frank E. Johnson, Jr.** (New Orleans Public Service, Inc., New Orleans, La.): This paper presents a solution to a problem which has always concerned everyone operating oil-filled transformers. Although the paper treats the subject almost exclusively on the basis of old transformers, it is evident that suitable design features could be incorporated in new transformers to allow the use of this method for the removal of acids and moisture as soon as formed. No doubt transformer manufacturers are cognizant of this, and will provide these facilities as soon as the demand arises.

With reference to the installation of an external tank on a 2,500-kva transformer, mention is made that the neutralization number increased about 0.20 in one year prior to treatment, and that 50 pounds of activated alumina were used for the 700 gallons of oil. Was this rate of increase typical for various sizes and types of transformers investigated? Fifty pounds of activated alumina is about one per cent of the weight of the oil treated. It therefore appears, for the case cited, that one per cent by weight per year would be required for a 0.20 increase in neutralization number. Referring to figure 3, the "initial acidity" figure was evidently about 0.55 prior to treatment, and 0.35 after treatment. Are these values independent of time, that is, could 100 pounds of activated alumina be used with a two-year interval between renewals?

If the weight required is proportional to the time, then another chart can be prepared from figure 3 which will be somewhat easier to interpret for a user desiring to stabilize, or hold his acidity at a given value. The same ordinates can be applied on the chart, but the abscissas can be given as "rate of increase of acidity per year." The independent curves then become "initial acidity" curves instead of "final acidity," and it is possible, knowing the rate of increase of acidity, to pick out the necessary quantity of activated alumina to eliminate the acidity increase.

Figure 1 in this discussion illustrates this point.

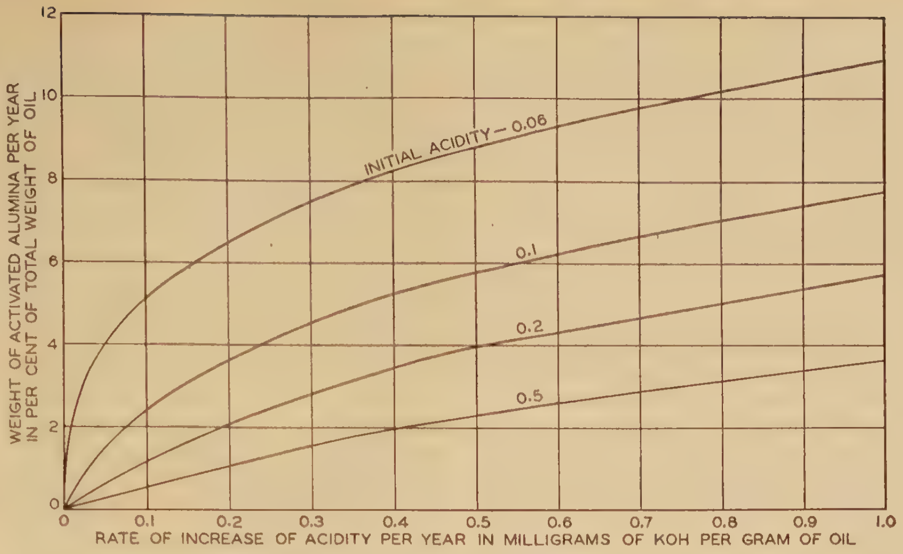

**Figure 1**

**T. H. Mawson** (The Commonwealth and Southern Corporation, Birmingham, Ala.): Oil reclamation at the present time is secured by several methods. This paper, by Mr. Housley, gives another method that has additional possibilities. Various schemes providing chemical neutralization with subsequent cleaning of the treated oil to remove the products of this reaction, together with sludge that can exist, will give oil that is satisfactory for reuse.

This particular paper deals with oil that has been used in transformers and bushings. It does not discuss the treatment of oil used in circuit breakers which is subject to considerably different service. Would there be any difference in the treatment of circuit-breaker oil?

In discussing one particular group of transformers which were operating continuously at a slight overload, and which were equipped with thermosiphon treaters, mention is made of an increase of 0.2 per year in neutralization number. If sludge begins to form when the neutralization number reaches 0.4, the full treatment with blotter press and other equipment should be used to reclaim this oil at intervals which depend upon an upper limit of acidity, or sludging, which has been previously determined.

This brings up the point of cost. Costs of reclamation from various sources vary from 3 to 12 cents per gallon for complete reclamation by other methods. For comparison the fixed charges on reclamation equipment plus the direct cost of labor and materials, plus the cost of oil, will determine the value of reclamation and the cheapest method.

The point should also be raised as to the value of reclaiming oil that has shown rapid deterioration when new. Cases on record show that certain oils which have met all of the usual specifications for new oil have not kept these properties for as long a time as other types of oil. After reclamation the same weaknesses appeared. Can any method be used that will make this oil satisfactory?

There are so many points involved on any system that the value of reclamation becomes a problem that is indigenous to that particular system. It must be solved on the basis of over-all costs covering a period of years. This paper gives a possibility of cost reduction, and, with an addition to the present experience of six years of such treatment, it is possible that these costs can be worked out to the satisfaction of all of the interested parties.

**C. F. Hill** (Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): The paper by Mr. Housley is quite important to many power companies due to the fact the extensive study of apparatus in service has made them conscious of the oil rejuvenation problem.

The author has called attention to one or two rather important advantages of the aluminum oxide, particularly its durability, lack of dusting, and finally, the ease of reactivation.

The statement is made that this new material is competitive with fuller's earth. It would be of considerable interest to have a detailed comparison of these two materials as to rate of reaction with the oil and other factors which control cost.

One statement in this paper does not agree with the usual notion of oil behavior. Normally, it is assumed that removal of the antioxidants by such filtering processes permits more rapid oxidation with further exposure of the oil. Housley states that the rate of oxidation does not speed up—or rather that the acid formation rate does not increase after removal of these acids by activated alumina. The question naturally arises as to the conditions of operation before and after the treatment.

It would also be of interest to know the cost of this reclaiming process per gallon of oil. There has been a considerable doubt if the cost would be reasonable, considering that the treated oil is not nearly a new oil.

One phase of this development which would appear to be quite attractive is the inclusion of the alumina on the transformer continuously. To keep the oil purified and dry at all times should be very desirable and appears practical.

**F. M. Clark** (General Electric Company, Pittsfield, Mass.): The many problems involved in the satisfactory reconditioning of used transformer oil bear close resemblance to the problems presented in the original refining of the material. Just as the original crude oil can be subjected to too much or too little refining treatment, so can the used oil be subjected to too little or too much reconditioning by means of the adsorbent used. The problem in the original refining of the oil is to remove those materials susceptible to easy oxidation and sludge formation while leaving untouched those original constituents of the oil which act as stabilizers and inhibitors of oxidation. The same problem confronts the application of adsorbents in the reconditioning of used transformer oils. In this case, the undesirable products are those formed as the result of previous oxidation and accompanying chemical change in the oil.

Mr. Housley presents two methods of maintaining transformer oil in suitably good condition during use. The first involves the treatment of the oxidized oil with activated alumina as, for example, by circulation through a bed of the material. Essentially this method is similar to the fuller's earth treatment of oil as a refining step in the original preparation of the material. The second method presented by Mr. Housley involves, during the use of the oil, its continuous gravity circulation through a bed of the activated alumina in accordance with the method of Cox who used fuller's earth in a similar manner.

In both methods of treatment, the objective of Housley appears to be the maintenance of the oil in a condition approaching the original oil color and acidity. It is generally recognized, however, that oil color and oil acidity are properties which in themselves are not safe gauges of sludge formation in transformer oil. Many oils can be obtained with equally low color and of neutral reaction but with widely varying rate of sludge formation in service. In fact, data accumulated indicate that the most severely adsorbent treated oil, that which first comes through the adsorbent bed, possesses the lowest color and is of neutral reaction, yet is characterized by a higher rate of sludge formation than later runnings from the same adsorbent bed, although these latter runnings may possess a much higher color and reaction value. Suitably low oil color and freedom from organic acidity are requisites for a properly treated transformer oil but appear to have no greater significance as a gauge of the sludge-forming properties in reconditioned oil than in the manufacture of the original oil at the refinery.

In his introduction, Mr. Housley states that it is possible to gauge the rate of oil deterioration by a study of the increase in oil acidity. With respect to sludge formation in transformer oil, this statement is only true in a general sense. Dependent on the type of oil and on the degree of refining as well as on the condition of oxidation in transformer use, sludge may form at low or high acid concentration. There appears to be no fixed relation between change in oil acidity and sludge formation in transformer oil which would allow the acidity value to be used as a gauge of the sludging character of the oil. Sludge formation is not a direct result of oil oxidation but appears as the product of a secondary reaction involving the polymerization of products formed in the primary oil oxidation. Among such products are the chemically unsaturated molecules formed as a result of oil oxidation but not capable of evaluation in a test for oil acidity.

Mr. Housley's paper presents no data concerning sludging properties. Sludge formation data are highly desirable and necessary in evaluating the serviceability of reconditioned transformer oils. The relation between the severity of the reconditioning treatment of the oil and the oil sludging tendency should be established. Data available appear to indicate that a used transformer oil, reconditioned by a properly selected and applied treatment with an adsorbent, although possessing many of the properties of a new oil such as low color and neutral reaction, does not possess the high degree of resistance to sludge formation normally associated with new transformer oil. It would be interesting and valuable were Mr. Housley to present data of this type on oils reconditioned by the use of activated alumina.

**J. E. Housley:** The interest shown by those giving discussions is greatly appreciated by the author. This problem of reconditioning insulating oils is certainly an important item on the maintenance program of any power system.

We have had no trouble from sludge in our circuit-breaker oils and in answer to Mr. Mawson's question, we have had no experience in treating these oils.

In the particular group of transformers to which Mr. Mawson refers, the use of a blotter press is avoided by removing the acid as it is formed and thus the oil is maintained below the sludging point. This is accomplished by the use of thermosiphon treaters.

As to the question of cost which has been raised in several of the discussions, it can be said that comparative costs of activated alumina treatment will differ according to local conditions. The cost of treatment per gallon of oil may be expected to range from 2.5 cents to 5.0 cents.

Mr. Johnson, in his discussion, presents an interesting relationship between the weight of activated alumina used and the time of treatment. There is a proportionality existing between the two and the curves, which he presents in his discussion, very clearly show this relationship. On one 2,500-kva transformer, 50 pounds of activated alumina has maintained 700 gallons of oil in good condition for $1^1/_2$ years. At this moment, we do not know how much longer this will maintain the oil. This particular transformer operates at a slight overload continuously.

In response to Mr. Battle's problem, it is suggested that the process of reducing the acid may be speeded up by more frequent reactivations, thus keeping the efficiency of the activated alumina at a maximum. The reactivating unit, shown in figure 5, is used both for treating and reactivating. However, I believe separate reactivation is more desirable, particularly when activated alumina is used to remove acid as formed (thermosiphon treaters) and where the reactivator is required for use on different batches of material.

We cannot answer Mr. Clark's statement regarding acidity and sludge formation specifically, but we have found acidity to be a good criterion of oxidation and sludging in our oils. Our experience has been that oils of fairly low neutralization numbers give no trouble from sludging.

**Transactions**

**Papers and Discussions Comprising Pages 179–242 of the 1939 Volume**

# Crossbar Dial Telephone Switching System

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IT IS the purpose of this paper to describe briefly the crossbar dial-telephone central-office switching system which has recently been developed by the Bell System for use in large cities. Sixteen years ago, in February 1923, a paper was read before the Institute, by E. B. Craft, L. F. Morehouse, and H. P. Charlesworth of the Bell System, which outlined the history and the problems involved in telephone central-office switching and described the panel dial central-office system which had just been developed and was being introduced in the large cities. The first central office of this type was placed in service in December 1921, and since that time 456 panel dial offices serving nearly $4^1/_2$ million subscriber stations have been installed in 26 different cities throughout the country. During these years many improvements have been made in the panel system to make it more serviceable to the telephone public and to meet the new problems which have arisen, but in addition, the engineers of the Bell System have continued their search to find new and better means for meeting telephone switching demands. This work has resulted in the adoption of the crossbar-type central-office switching equipment. Two offices of this type were placed in successful operation during 1938 and others are in process of manufacture and installation.

It will be appreciated that for large metropolitan areas, the development and economic introduction of a central-office switching system which differs materially from the existing systems is a rather large undertaking. The system must fit into the existing plant as a whole without material change. Generally any important changes affecting the subscribers' use of the telephone or the methods used by switchboard operators should be avoided. Existing numbering plans should not be affected, existing classes of service should be continued, and the addition of others made feasible in case they should be required.

All of these and many other factors have been taken into account and all requirements have been met by the crossbar system which offers important improvements in telephone switching, both in operation and maintenance. Its introduction does not make any of the existing equipments obsolete in the sense that these equipments will be less serviceable nor will it cause their replacement. Central offices of the crossbar type can be installed in the same building with existing panel central offices without loss in operating economies in either type of office. Certain equipment, such as the existing and additional outgoing trunks to other central offices, manually operated switchboard positions, operating room and maintenance desks, power plant and alarms, can be used in common by the two types of offices in the same building.

## General

Before describing the crossbar system it is desirable first to give a brief outline of the principal functions of a dial central-office equipment. Such an office is capable of serving 10,000 subscriber line numbers, and is provided with a sufficient number of connecting switches, trunks, and associated circuits so that under usual peak loads of traffic, calls will be completed promptly.

The central-office circuits, in response to the lifting of the receiver by the calling subscriber, connect the subscriber line to the switching equipment. This equipment then extends the calling line, "link by link," through several switching stages to the called line as determined by the called office code and line number dialed by the calling subscriber. When the connection has been established to the called line, the subscriber bell is rung and when the subscriber answers, the talking connection is completed. During the conversational period the connection is held under control of the calling telephone, and when the telephone receivers are replaced, the central-office equipment and the telephones are released for use on other calls. The equipment, of course, transmits the busy-tone signal to the calling subscriber if the called line is found busy, and automatically routes a call for a discontinued or an unassigned line to an operator who informs the subscriber of the status of such a line.

Operators and associated switchboards are provided in the dial system to handle certain classes of calls and to render assistance to subscribers when required. Calls to these operators are established in response to the dialing of operators' codes in a manner similar to the establishment of calls to other subscribers.

Operators are usually provided to complete calls terminating in a dial office which are originated by subscribers served by manual offices.

Prior to the introduction of the crossbar system, the Bell System employed two general types of dial central offices. These are the well-known step-by-step and panel systems.

The step-by-step system has been used generally in the smaller cities which are frequently served by a single central office or by a relatively small number of offices and where the trunking problems are consequently less complicated. The switches of the step-by-step system are controlled directly by the impulses from the subscriber dials and, necessarily in conformity with the dial, the system operates on a decimal basis. The selectors of this system are first moved under control of the dial to any one of ten vertical positions, corresponding to the numeral of the digit dialed, and in the case of trunk hunting switches, is then automatically rotated over a row of ten trunk terminals to find an idle trunk during the interdigital time of the dial.

The step-by-step switch thus has access to ten different groups of trunk terminals with ten terminals each. The location of the trunk groups on the switches is governed by the digits dialed and consequently the relocation of a

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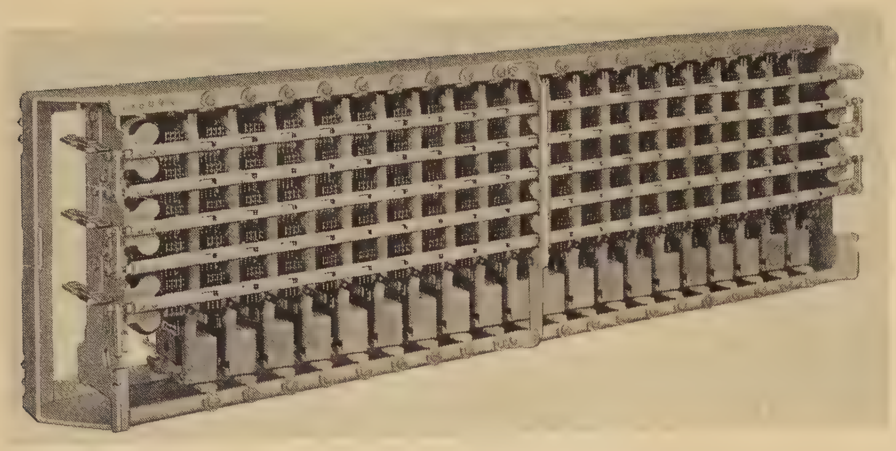


Figure 1. Crossbar switch—front view

group necessitates directory changes. These limitations in trunk access and flexibility are not material handicaps in the smaller cities throughout the country where the system is giving excellent service.

The panel system meets the complex service requirements of the larger cities with their large volume of traffic and multiplicity of central offices. In these cities the number of trunk groups is large and the number of trunks in the groups varies widely. Further, the number of groups and their sizes are frequently changed by the introduction of new offices and changes in the character or extent of existing central-office areas.

In the panel system, senders are provided which record and store the dial pulses as they are dialed and then independently control the operation of the switching units. The large panel-type switches provide access to large groups of trunks and to a large number of groups, and at the same time permit considerable variation in the sizes of the groups. The necessary flexibility in the size and location of the trunk groups is obtained by flexibly wired routing equipment provided in decoder circuits which are associated with the senders. These facilities permit trunk group locations on the switches as dictated by traffic regardless of the office codes listed in the directories and dialed by the subscribers. The panel system also readily provides for the routing of calls through intermediate or tandem offices where the traffic between offices can be more economically handled in this manner.

The crossbar system also makes use of the sender and decoder method of operation and provides a still greater flexibility in the trunking arrangements than is obtained by the panel system.

## The Crossbar System

The two outstanding features of the crossbar system are the "crossbar switch" which is used for all major switching operations, and the "marker" system of control which is used in the establishment of all connections throughout the crossbar office.

The crossbar system is essentially a relay system employing simple forms of relays and relay-type structures for all switching operations. The apparatus consists almost wholly of crossbar switches, multicontact relays, and the usual small relays similar to those generally employed in all telephone systems. The switching circuits are wired to the contacting springs of the switches, and the connections through the switches are made by pressing contacts together by means of simple electromagnetic structures instead of the moving brushes and associated fixed bank terminals of other systems.

The use of relay-type apparatus with its small, pressure-type contact surfaces economically permits the use of twin or double contacts with thin layers of precious metal for all contact points. Obviously, double precious metal contacts make for reliable operation, especially with the low speech and signaling currents inherent to a telephone system.

The short mechanical movements and the inherently small operating time intervals of the "relay-like" crossbar switch permits the use of common circuits or "markers" to control the operation of the switches. This has permitted the use of large assemblies of switches and associated relays on unit frames which can be wired and completely tested for operation in the factory before the units are shipped.

In the design of the switching frames and associated control circuits, one of the objectives realized has been the standardization of a relatively small number of different types of equipment units, thereby simplifying manufacture and merchandising. This also simplifies the engineering of the equipment by the telephone companies in the preparation of their specifications to meet the particular traffic requirements of the various central offices.

The marker system used for controlling the switching operations has many advantages, the more important of which will be disclosed later in the general description of the operation of the equipment. It might be mentioned here, however, that the marker is an equipment unit consisting almost entirely of relays, which completes its functional operations in the establishment of a call in a fraction of a second. This short operating time permits a few markers to handle the entire traffic in the largest office. The markers are connected momentarily by means of multicontact relays to the various switching units of the office to control the establishment of the calls through the crossbar switches.

An outstanding advantage of the marker system of control is the "second-trial" feature, by means of which two or more attempts can be made to establish a call over alternate switches and trunks when the normally used paths are all busy. The markers are arranged to detect short-circuited, crossed, grounded, and open-circuit conditions at all vital points, and before releasing from a connection they make circuit checks to insure that the connection has been properly established. When trouble conditions are detected, they make a second attempt to complete the connection, after sounding an alarm and recording the location and nature of the trouble encountered. The marker system facilitates the introduction of new service features and changes in operation, which may be found desirable from time to time, due to the fact that the principal controlling features of the entire system are vested in a small number of markers.

## Apparatus

### Crossbar Switch

The crossbar switch from which the system derives its name is the basic switching unit of the system. Figure 1 shows the front view of a 200-point crossbar switch.

Fundamentally this switch consists of three major functional parts: (*a*) 20 separate vertical circuit paths, (*b*) 10 separate horizontal circuit paths, and (*c*) a mechanical means for connecting any one of the 20 vertical circuit paths to any one of the 10 horizontal circuit paths by the operation of electromagnets. From a structural viewpoint the switch is comprised of a rectangular welded frame on which are mounted 20 vertical units and the selecting mechanism consisting of 5 horizontal bars operated by 10 selecting magnets.

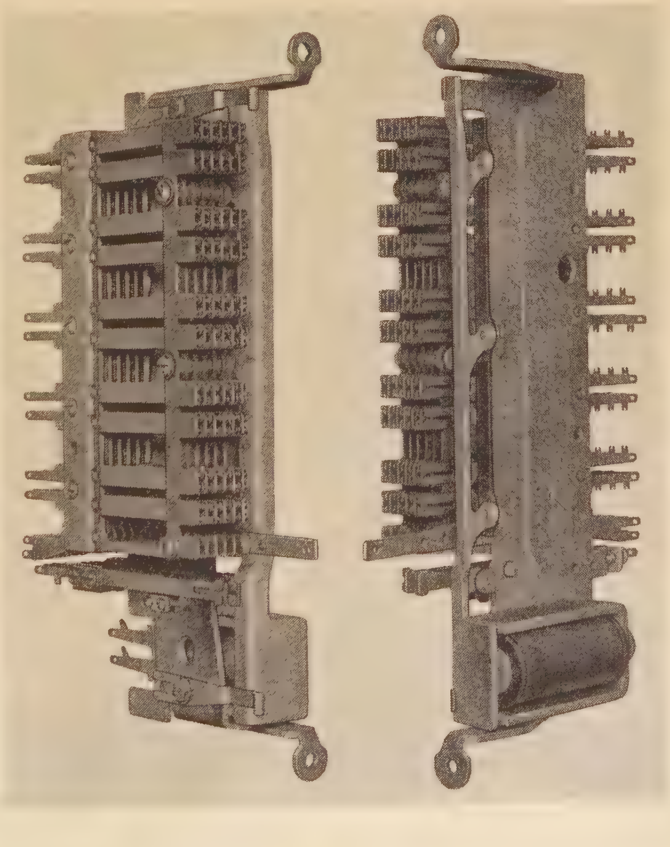
Primarily the switch is a multiple relay structure with 20 vertical relay-like units, each unit having an operating or "holding" magnet and ten sets of contacts in a vertical row. The switch arrangement provides a rectangular field of contacts in 20 vertical rows and 10 horizontal rows or a total of 200 sets of contacts, one set at each "crosspoint." These crosspoint contacts are operated independently of each other by a coordinate operation of the horizontal and vertical bars. The horizontal bars are controlled by the 10 horizontal or "selecting" magnets and the vertical bars by 20 vertical or "holding" magnets. Any set of contacts in any vertical row may be operated by first operating the selecting magnet corresponding to the horizontal row in which the set of contacts is located, and then by operating the holding magnet associated with the vertical row. Since the contacts are held operated by the holding magnet alone, the selecting magnet is operated but momentarily and is released as soon as the holding magnet is operated. After the selecting magnet is released, other connections may be established through the switch by the operation of other selecting and holding magnets. It is thus apparent that ten connections can be established through the switch, one for each of the horizontal paths.

From figure 2 the rather simple mechanical interlocking of the horizontal and vertical bars which causes the operation of a set of crosspoint contacts will be understood. The ten sets of contacts in a vertical row are associated with the vertical or "holding" bar of the row. Each horizontal or "selecting" bar is provided with 20 selecting fingers which are made of flexible wire. These fingers are mounted at right angles to the bar, one at each of the vertical rows of contacts. Thus when a selecting bar is rotated through a small arc by its magnet, the selecting fingers will move up or down into a position so that when a holding bar is operated by its magnet, it will engage the selecting finger at the crosspoint of the two bars and cause the corresponding set of contacts to operate. The selecting bar and the fingers not used will then be released when the selecting magnet is released, but the selecting finger used to operate the selected set of crosspoint contacts will remain latched and the contacts held closed by the holding bar until the holding magnet is released at the end of the connection. The selecting fingers are each provided with a damping spring to reduce vibration on the operation and release of the fingers.

It will be noted that the selection operation is performed by five horizontal bars although there are ten horizontal rows of contacts. This is accomplished by operating the bars in either of two directions. As shown in figure 1, two magnets are associated with each bar, one whose armature is on top of the bar, the operation of which causes the selecting fingers to move in a downward direction, and the other whose armature is below the bar causing the fingers to move upward. The selecting bars are restored to the normal or mid-position by the centering springs located on the end of the switch adjacent to the magnets.

Figure 3 shows the vertical unit of the crossbar switch with its ten sets of normally open "make" type contact springs, the holding magnet at the bottom, and the long vertical armature to which is attached the vertical holding bar. The vertical unit shown has six pairs of contacts at each of its ten crosspoints. Other vertical units are provided with ten sets of three, four, and five pairs of contacts per set. One spring of each pair as shown is a fixed spring consisting of a projection of an insulated vertical metal strip, made in the shape of a comb. This strip extends from the top to the bottom set of contacts of a vertical row. Wiring lugs are provided at the lower end of these vertical strips facing the rear to which are wired the lines or trunks of the vertical circuit paths. At the lower end of these strips and facing the front is another projection used by the maintenance force for testing purposes. The mate or movable spring of each pair is individually insulated from all other springs. These springs extend to the rear of the switch for wiring purposes and may be strapped horizontally to the

**Figure 3. Crossbar switch vertical unit**



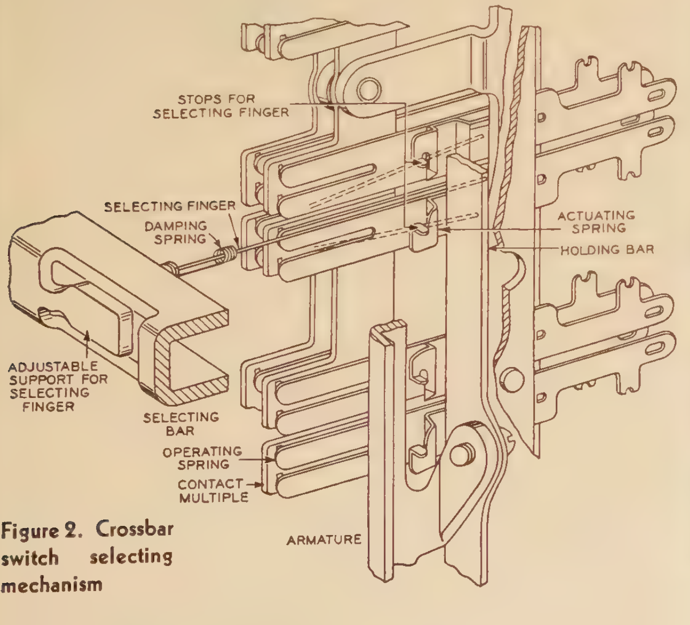
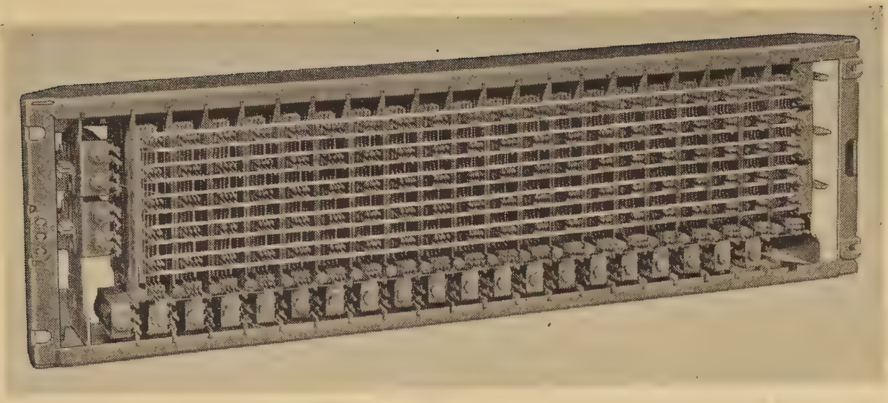


**Figure 2. Crossbar switch selecting mechanism**



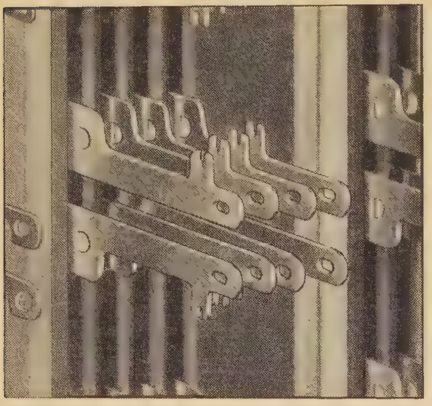


Figure 4. Crossbar switch—rear view

corresponding springs of adjoining vertical units to extend the horizontal circuit path through the switch.

The contacting ends of the thin movable contacting springs are bifurcated to provide two flexible contacts in parallel. The contacting surfaces on these springs as well as the mating fixed springs are provided with a thin layer of palladium. The use of the double precious metal contacts is an important feature of the crossbar system in providing more reliable contacting surfaces. Experience has shown that the chance of simultaneous failures of both contacts of a pair is extremely small. The actual contacting surfaces of each pair of springs consist of small bars of contact metal located at right angles to each other. These bars are composed of a ribbon of nickel capped with a thin layer of palladium. This crossbar arrangement of contacts provides a rather large area over which the two springs can make contact with each other, and thereby permits considerable tolerance in the manufacture and adjustment of the contact spring assemblies.

The switch may be equipped with "off normal" contact spring assemblies. When these are furnished they are associated with each selecting or holding magnet and are operated like relay contacts when the associated magnet operates, regardless of which crosspoint contact is closed. They are used to perform circuit functions as required in the various uses of the switch.

In the design of the switch special attention was given to the problem of wiring and cabling. Figure 4 shows the wiring terminals on the rear of the switch. These terminals are arranged for individual wiring and also have staggered, notched projections so that the terminals can be readily strapped together horizontally with bare wire as shown. This is an important feature of the switch since it permits a multiple of terminals to be easily soldered together and reduces the wire congestion on the switch.

The 200-point crossbar switch is $9^1/_4$ inches in height and $30^1/_2$ inches in length. In addition a 100-point switch $20^1/_2$ inches in length is provided. This switch is similar to the 200-point switch but is equipped with ten vertical units.

## Multicontact Relay

The multicontact relay used in the crossbar system is shown in figure 5. It resembles in design the vertical unit of a crossbar switch. The relay is provided in four sizes in respect to the number of contacts, namely, in 30, 40, 50, and 60 sets of individually insulated contacts, all of which are of the normally open type which are closed when the magnets of the relay are operated. Each relay is provided with two separate magnets, armatures, and associated groups of springs, and both magnets are energized in parallel in order to close all of the contacts. By operating the two magnets independently the structures can be used as two separate relays, each equipped with 15, 20, 25, or 30 sets of contacts. The relay occupies a mounting space approximately 2 inches by 11 inches and is provided with a cover.

All contact springs are equipped with twin contacting surfaces similar to the contacts used on the crossbar switch except that they are composed of solid bars of precious metal due to the heavy-duty requirements. To facilitate wiring, these relays are manufactured with two types of wiring terminals. In one type the movable springs are of graduated lengths and are provided with notched lugs for bare wire strapping to permit the multipling of springs horizontally to corresponding springs on other relays mounted adjacent. In the second type the strapping lugs are omitted and all springs are of the same length and are provided with soldering eyelets for individual or nonmultiple wiring.

The multicontact relay finds its chief use in the common connector circuits where a large number of leads must be connected simultaneously to a common circuit.

## U- and Y-Type Relays

New and improved general-purpose small relays which have been coded the *U* and *Y* type are used in this system. Figure 6 shows a typical *U*-type relay. Although somewhat similar to the *E*- and *R*-type relays which have been in common use in the telephone systems for many years, it differs from them principally in that it has a heavier and more efficient magnetic structure which permits the use of a greater number of contact springs. These relays permit the use of spring assemblies up to a maximum of 24 springs in various combinations of springs, including transfer contacts and simple make and break contacts. The relays are constructed of relatively simple parts, most of which are blanked and formed in the desired shapes in the same manner as the earlier *E*- and *R*-type relays. The cores are made from round stock and are welded to the mounting bracket of the relay. The structures of all of these relays are similar and differ principally in their spring assemblies and windings.

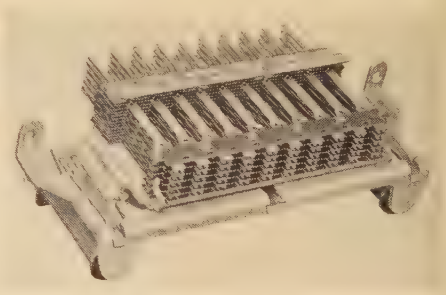


Figure 5. Multicontact relay

In order to insure more reliable contact closures, the relays are equipped with twin contacts. Various types of contact metal and sizes of contacts are provided, depending upon the characteristics of the circuit controlled by the contacts.

Improved methods of clamping the prings in their assemblies, together with he design of the springs, provide sta-ility and minimize manufacturing and naintenance adjusting effort.

Contacts practically free from chatter n both the operation and release of the relay have been obtained by the use of relatively heavy stationary springs, short thin movable springs, and a pivoted arrangement of the armature suspension. By reference to figure 6 it will be seen that the rear ends of the armature are pivoted by two pins which project through holes in the hinge bracket mounted on the rear spring assembly. In the earlier flat-type relays of the *E* and *R* type, the armature was suspended at the rear by means of a reed-type armature hinge.

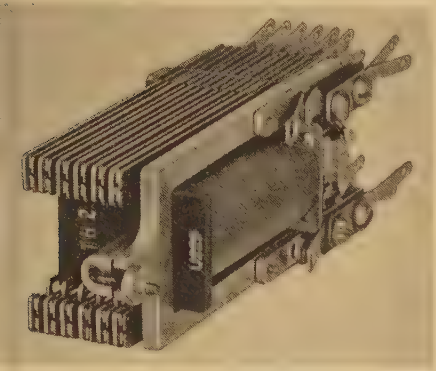


**Figure 6. U-type relay**

The *Y*-type relays make use of the same manufacturing tools and processes as the *U* type. Copper or aluminum sleeves are provided over the cores beneath the windings to secure the slow release characteristics required on these relays. The relay armature is embossed so that when the relay is operated, satisfactory contact is made between the metal surfaces of the magnetic circuit which insures uniform time characteristics.

In both the *U*- and *Y*-type relays the cylindrical cores permit the use of form-wound coils which are wound on special machines and slipped over the cores when completed. In the manufacture of these coils a removable mandrel is used. It is covered with a layer of sheet cellulose acetate and accommodates several coils. These coils are then automatically wound on the mandrel from different spools of insulated wire. Separations are left between adjacent coils so that when the winding operation has been completed the individual coils can be separated. A very thin sheet of cellulose acetate is automatically interleaved between successive layers of wire to hold the wire in place and to provide insulation between layers. This general method of winding coils also is used for the magnets of the crossbar switches and multicontact relays.

## Functions of the Equipment Units

The general operation of the system as a whole may be more easily understood by first describing the principal equipment units in the system and their functions before proceeding with a description of the operation of the circuits. A simplified block diagram of the principal equipment units of the system is shown in figure 7. It will be noted that in general there are three types of equipment units:

1. The transmission battery supply and supervisory circuits consisting of the "district junctors" and the "incoming trunks."
2. The crossbar-switch frames.
3. The common "control" circuits, the "senders," and the "markers."

The "district junctor" and the "incoming trunk" circuits are composed principally of small relays. The district junctors furnish the talking battery for the calling subscribers and supervise the originating end of connections. The incoming trunks control the ringing of the called subscriber bells, furnish talking battery for the called subscribers, and supervise the terminating end of connections.

The switch frames, which consist almost entirely of crossbar switches, provide the means for switching between the subscriber lines, the district junctors, and the incoming trunks. Switch frames also are used for switching the district junctors and the incoming trunks to the senders.

The "senders" consist principally of small relays and their functions are similar

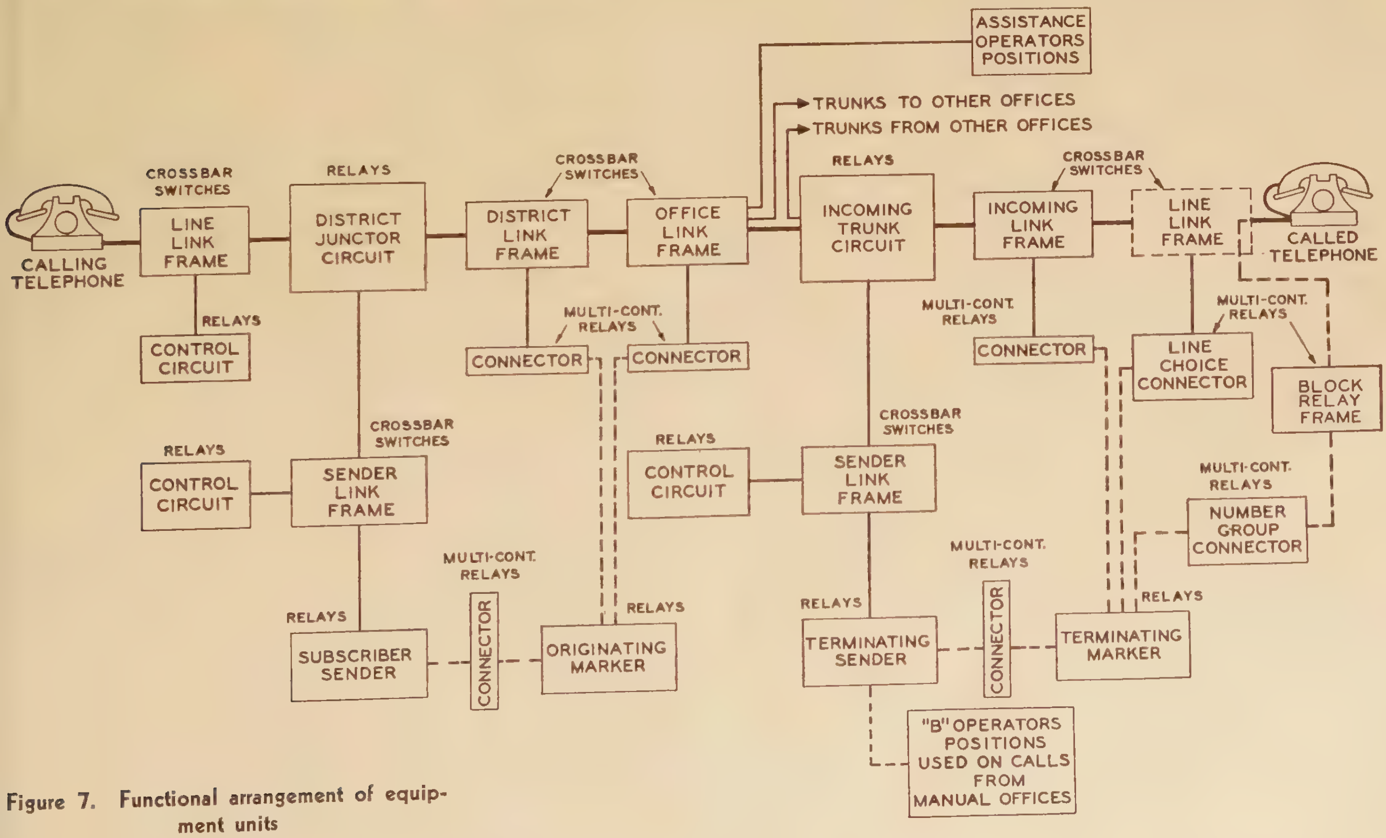


**Figure 7. Functional arrangement of equipment units**

to those of the operators at a manual switchboard. The "subscriber senders" register the called numbers from the subscriber dials and transmit the necessary information to the "markers," to the "terminating senders," and to the manual operator positions in manual offices for completing connections to the called lines.

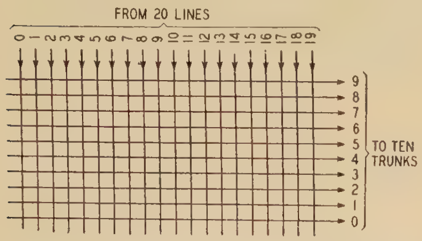


**Figure 8. Simple trunking arrangement with a single 200-point crossbar switch**

The subscriber senders also control the operation of the selectors in distant panel offices. The "terminating senders" in the terminating end of the crossbar office receive the numerical digits of the called numbers from the subscriber senders of any dial office and transmit the required information to the "terminating markers" for setting up the connections to the called lines.

The "markers" are the most important control circuits in the system. They are composed of both small and multicontact relays. There are two types, one for originating traffic and one for terminating traffic. The operating time of the markers is short, considerably less than one second, and consequently only three or four markers of each type are required in the average office.

The "originating markers" determine the proper trunk routes to the called office. They have access to all outgoing trunk circuits and all the crossbar-switch frames that are used for establishing the connections to the called office trunks. They test the trunk group to find an idle trunk to the called office, and also test and find an idle channel through the switch frames, and finally operate the proper selecting and holding magnets of the crossbar switches to establish the connections from the subscriber line to the trunk circuit.

The "terminating markers" perform similar functions in the terminating end of the office to set up the connection from the incoming trunk circuit to the called subscriber line. They have access to all of the subscriber lines terminating in the office, and to all crossbar-switch frames used for connecting to subscriber lines. They test the called line to determine whether it is idle, and also test for and find an idle channel through the switch frames and finally operate the proper magnets of the crossbar switches and establish the connection to the called subscriber line.

In addition there are common "control" circuits associated with the "line link" and the "sender link" frames for controlling the operation of the switches on these frames. There are also the common "connector" circuits, consisting mainly of multicontact relays, which are used for connecting the markers to the senders, to the switch frames, and to the test terminals of the called subscriber lines.

It should be noted that the line-link frames, although shown separately, are used for both originating and terminating traffic.

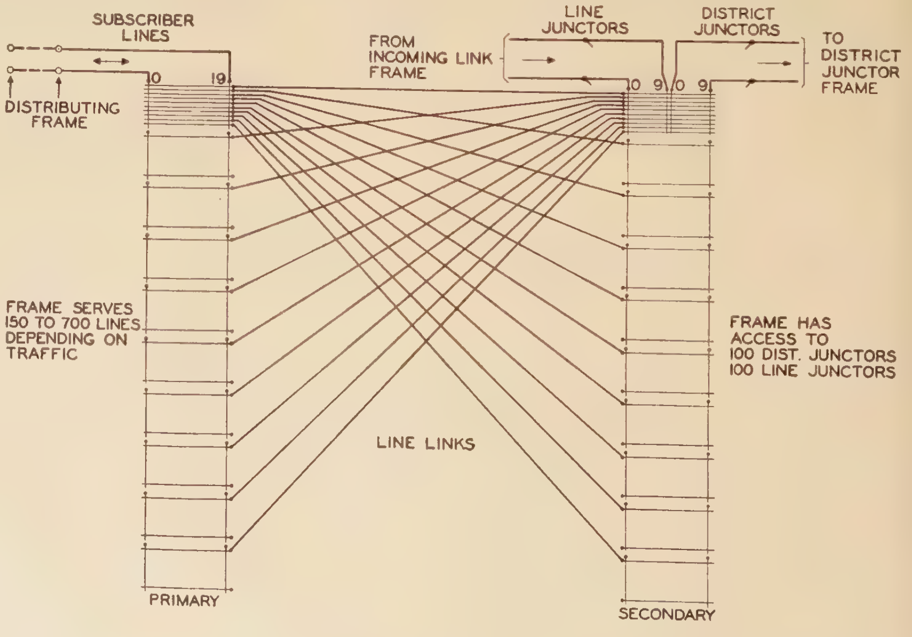
After the talking connection has been established between two subscribers, all of the common control units, such as the senders, markers, connectors, line-link control circuit, and the sender-link frames and their associated control circuits, will have been released, and the talking connection will be maintained in this condition by the holding magnets of the crossbar switches used on the line-link, district, office, and incoming-link switch frames. These switch magnets are held operated under control of the supervisory relays in the district junctor and the incoming trunk circuits and are released when the subscribers replace the receivers.

## Trunking Arrangements

The fundamental method of using the crossbar switch for setting up connections is illustrated in figure 8. This figure shows a 200-point crossbar switch with 20 vertical units each wired to a subscriber line and ten trunks strapped horizontally across the switch. With such an arrangement, any one of the 20 lines may be connected to any one of the ten trunks. The number of lines which can be connected to the same ten trunks may be increased to 40 by adding a second 200-point crossbar switch with 20 different lines connected to its verticals and by wiring the horizontal contact multiple of this second switch to the horizontal multiple of the switch shown in figure 8. By adding other switches in this manner, any number of lines may be given access to the ten horizontal trunks.

To obtain greater trunking access, two groups of switches known as "primary" and "secondary" are used. Figure 9 illustrates this primary- and secondary-switch arrangement as used in the line-link switch frames and in various forms throughout the crossbar office. The switches are arranged in two vertical files of ten primary switches and ten secondary switches. There are 20 subscriber lines connected to the verticals of each of the ten primary switches and 20 trunk circuits are connected to the 20 verticals on each secondary switch. The horizontal multiples on the primary switches are connected to the horizontal terminals of the secondary switches, each primary switch having one horizontal path connected to each of the ten secondary switches. With this arrangement, the 20 lines of any primary switch have access to all 200 trunks connected to the secondary switches. Since all of the pri-

**Figure 9. Primary-secondary trunking arrangement**


SUBSCRIBER LINES
DISTRIBUTING FRAME
0
19
FROM INCOMING LINK FRAME
LINE JUNCTORS
DISTRICT JUNCTORS
0
9
0
9
TO DISTRICT JUNCTOR FRAME
FRAME SERVES 150 TO 700 LINES DEPENDING ON TRAFFIC
FRAME HAS ACCESS TO 100 DIST. JUNCTORS 100 LINE JUNCTORS
LINE LINKS
PRIMARY
SECONDARY

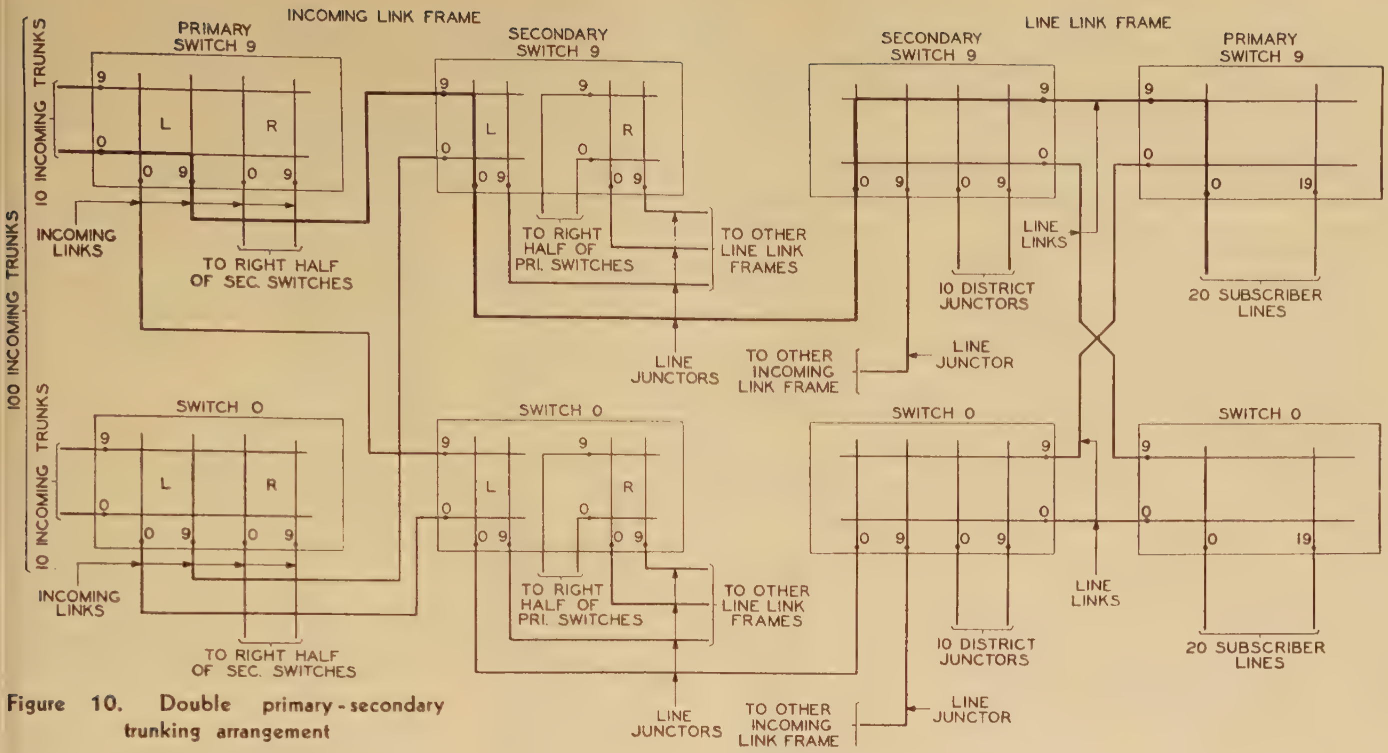


**Figure 10.** Double primary-secondary trunking arrangement

mary switches are wired in this manner, that is, with their ten horizontal paths distributed over the ten secondary switches, then all of the 200 lines on the primary switches have access to the 200 trunks on the secondary switches. It is evident that another vertical file of ten primary switches may be added with 20 subscriber lines connected to the verticals of each switch, and with the horizontal paths strapped and connected to the horizontal paths of the primary switches shown. This would give 400 lines access to the 200 trunks on the secondary switches. In actual practice on a line link frame, several files of primary switches may be connected together in this manner depending upon the traffic volume of the subscriber lines. The circuit paths connecting the horizontal rows of terminals of the primary switches to the horizontal rows of terminals of the secondary switches are called "line links."

To establish a path from a line circuit on a primary switch to a trunk circuit on a secondary switch, the common "control" circuit serving this line-link frame locates the subscriber line to be served and then simultaneously selects an idle "line link" on the primary switch on which the subscriber line appears and a group of trunks wired to a secondary switch in which there are one or more idle trunks. Thus the selection of the line link is made contingent upon the availability of trunks, and by means of this together with the primary-secondary distribution of the links a very efficient usage of the links and trunks is obtained.

In the line-link frame shown in figure 9, it will be seen that the trunks on the verticals of the secondary switches are split into groups of 100 trunks each, one group being connected to the "district junctors" and used for originating traffic and the other group of 100 trunks being connected to "line junctors" and used for terminating traffic.

It will be noticed that there is but one crossbar-switch appearance of a subscriber line in the office. This is on a vertical unit of a primary crossbar switch where both the originating and terminating calls are completed by means of the same line-link circuits. Thus all originating traffic from any of the 20 lines on any primary switch flows through the associated ten line links to the 100 district junctors and all terminating traffic to these 20 lines flows through the same ten line links from the 100 line junctors.

This single "primary and secondary" trunking arrangement also is used at other points in the system, such as in the originating and terminating sender-link switch frames, where the circuits reached are nondirectional, that is, where any one of the selectable circuits wired to the frame can be used for setting up a connection.

For the switch frames where the circuits reached are directional, that is, where a particular called line or a particular group of trunks must be used in order to complete a connection, the problem of trunking becomes more complex and it is necessary to provide a trunking arrangement using two "primary and secondary" switch frames arranged in tandem.

Figure 10 shows a typical arrangement of this kind which is necessary to secure the required trunking flexibility and efficiency. This figure shows an "incoming link" frame to which incoming trunks are connected and a "line link" frame to which subscriber lines are connected as described above. These two frames are used in tandem for establishing the terminating connections between the incoming trunks and the called subscriber lines. As is indicated, 100 incoming trunks are connected to the 100 horizontal paths of the ten incoming link frame primary switches, there being ten incoming trunks connected to each of the primary switches. A total of 150 to 700 subscriber lines may appear on the verticals of the primary switches of the line-link frame; however, only 200 lines or 20 on the verticals of each of the ten primary switches are shown in the figure.

In order to connect a particular incoming trunk to a particular called line, an idle channel is selected through these two switch frames, consisting of an "incoming link" on the incoming-link frame, a "line junctor" between the two frames, and a "line link" on the line-link frame, and all are connected in series as shown in the figure. It will be noted that the incoming trunks on each of the primary switches have access to 20 incoming links appearing on the 20 verticals of the switch. These 20 incoming links are distributed over the ten secondary switches of the frame, 2 links being connected to each switch, one to each half switch. It will be observed that in order to provide for the distribution of the 20 incoming links over the ten secondary switches, the horizontal paths of the secondary switches are separated between the tenth and eleventh verticals, thus taking advantage of the flexibility of the crossbar switch by providing 20 horizontal paths instead of ten on each switch. The incoming links, on each half of these secondary switches, have access to "line junctors" appearing on the verticals of these switches. These line junctors are in turn distributed over the secondary switches of all the line-link frames in the office. There will be at least one line junctor as shown, from each secondary switch on an incoming link frame to a secondary switch on every line-link frame in the office, or a minimum of ten line-junctor paths between any incoming-link frame and any line-link frame. The number of the line junctors between these frames will vary depending upon the number of frames required in an office. The line junctors on the verticals of each of the line-link frame secondary switches in turn have access to ten line links on the horizontal paths. These ten line links are, as described above, distributed over the primary switches of the line-link frame, one to each primary switch. These line links then have access to the called subscriber lines which appear on the verticals of the primary switches. With this arrangement of switches and the three groups of interconnecting link paths, any incoming trunk can be connected to any called line on the line-link frame shown, or by means of other groups of line junctors, to a called line on any other line-link frame in the office.

Terminating markers are employed for selecting the paths through these switches to connect an incoming trunk to a called subscriber line. The marker, as will be explained later, records information which permits it to connect to the test wire and holding magnet of a called line and to the test wires and switch magnets of the groups of incoming links, line junctors, and line links through which the incoming trunk may be connected to the called line. The marker simultaneously tests these three groups of paths and "marks" an incoming link, a line junctor, and a line link which are idle and are accessible to one another, and then operates the switch magnets to connect these three paths and the incoming trunk and the called line together. The paths are selected in an ordered arrangement, so that the lowest numbered incoming links, line junctors, and line links are preferred and are used as long as they are available. This increases the efficiency of the paths as compared with a random selection, since it reduces the chance that one or two of them although idle cannot be used because the third one is busy.

A double primary and secondary trunk arrangement similar to the one shown in figure 10 is employed for connecting district junctors to outgoing trunks in the originating end of the office.

## BRIEF DESCRIPTION OF CIRCUIT OPERATION

The operation of the system will be described by tracing the progress of a call through the system. The establishment of a call from one crossbar subscriber to another crossbar subscriber may be divided into four stages: two in the originating end of a connection and two in the terminating end.

1. The calling subscriber is connected to a sender for the purpose of registering the called number which is dialed.

2. The subscriber sender is connected to

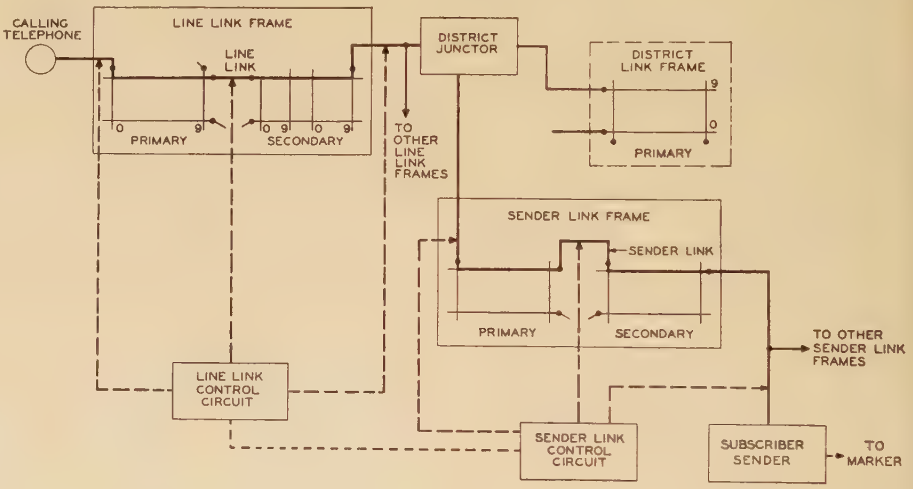


Figure 11 (above). Calling line connected to district junctor and subscriber sender

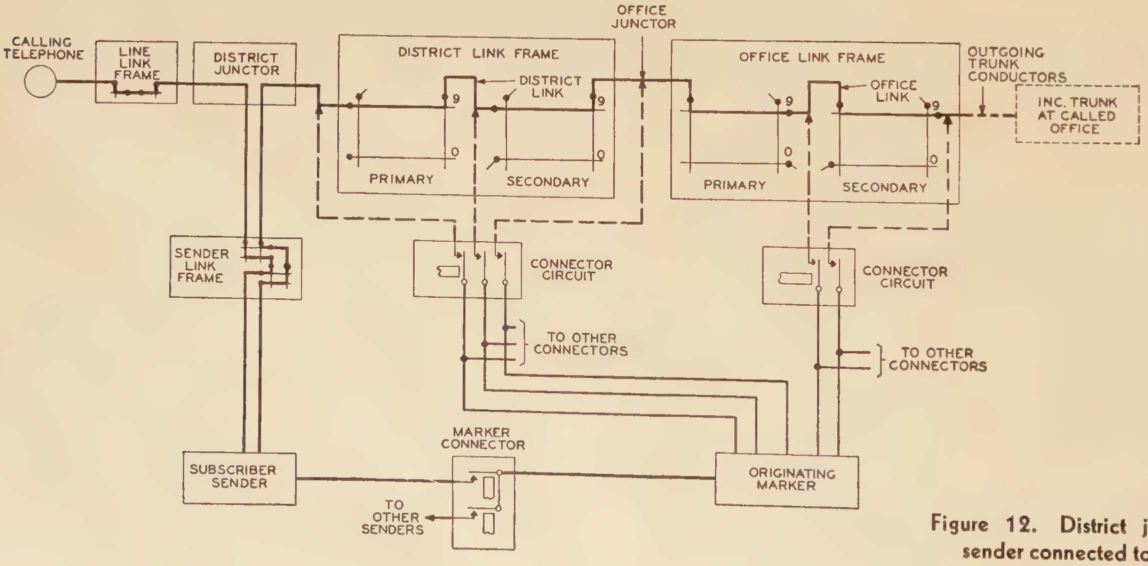
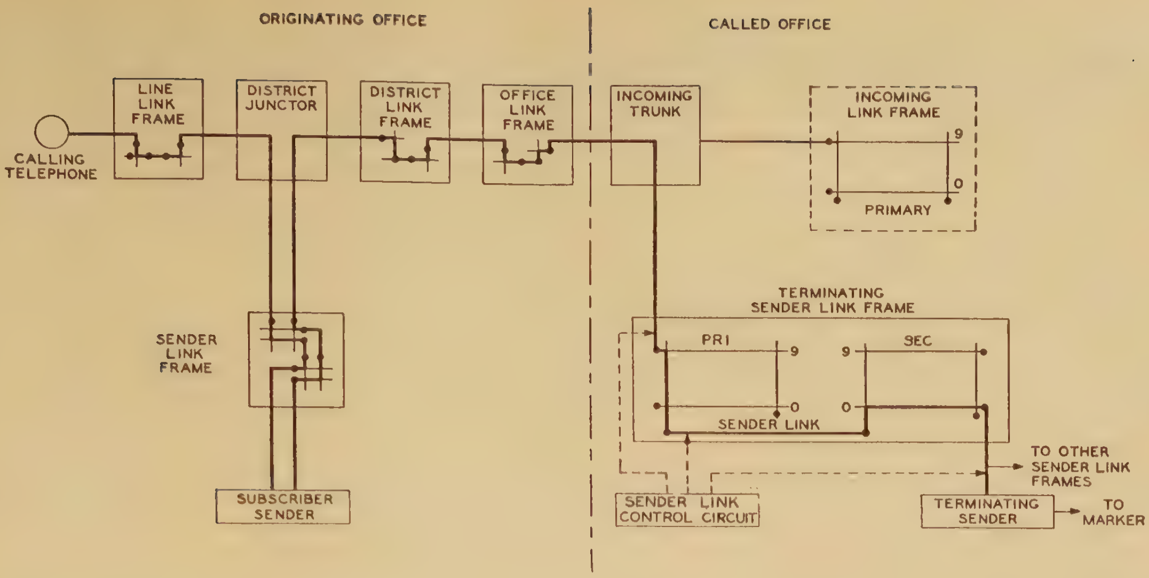


Figure 12. District junctor and subscriber sender connected to the outgoing trunk

**Figure 13. Connection established to terminating sender**



an originating marker and the marker selects the switch frames for establishing the connection to an outgoing trunk.

3. The outgoing trunk circuit is connected to a sender in the terminating end to register the called number.

4. The terminating sender is connected to a terminating marker and the marker selects the switch frames for establishing the connection to the called subscriber line.

The first stage in the progress of a call is illustrated in figure 11. It will be seen that the line of a calling subscriber terminates on a vertical unit of a primary crossbar switch located on a line-link switch frame. When the subscriber receiver is lifted from the telephone preparatory to dialing, a line relay is operated, as in other systems, and the circuits proceed with the establishment of the connection to an idle subscriber sender which will register the called number when it is dialed.

The circuit functions on this stage of the call are as follows:

1. The subscriber line is located by the "line link control" circuit which is common to the line link frame, by a co-ordinate method of testing. That is, the control circuit determines the primary crossbar switch in which the line is located and the particular vertical unit in the switch on which the line is terminated. This operation is similar to the line-finder operation in other dial systems, except that the operation is accomplished by relay operations instead of by a mechanically traveling brush.

2. The line-link control circuit then simultaneously selects an idle line link between the primary switch in which the line appears, and a secondary switch on which a group of district junctors appears which has at least one idle district junctor in the group and which has access to idle senders and an idle sender link.

3. This will bring into operation the common "sender link control" circuit of the sender-link switch frame to which the selected group of district junctors is connected. This control circuit will select an idle district junctor in this group which appears on a primary switch on the sender-link frame. There are ten sender links serving the selected district junctor. These ten sender links and the ten sender groups to which they have access on the secondary switches are then tested simultaneously to find an idle sender link with access to a group of senders in which there are one or more idle senders. When this choice has been made an idle sender in the group is then selected.

4. The two control circuits in co-operation with each other operate, first the selecting magnets and then the holding magnets associated with the paths selected on the switches of both the line-link and sender-link frames, and thereby establish the connection from the calling subscriber to an idle subscriber sender.

This connection may be traced by referring to figure 11, from the calling line on the vertical unit on a primary switch of the line-link frame, through a line link and a secondary switch, through a district junctor circuit, to a vertical unit on a primary switch of the sender-link frame, through a sender link and a secondary switch to a subscriber sender which is connected to a horizontal circuit path on the secondary switch.

5. The two control circuits are then released and made available for use on other calls. The connections through the switches to the sender are held established by means of the holding magnets which are held operated over a signal control lead, called the "sleeve" lead, under control of the relays in the sender, which in turn are under control of the subscriber telephone.

Upon completion of these operations which take but a fraction of a second the subscriber sender transmits the dial tone to the calling subscriber as an indication to dial the number. When the subscriber dials, electrical impulses are transmitted to the sender, which receives and registers them. When the sender has registered the office code, which in New York City for example is contained in the first three digits dialed, the sender will connect itself to an idle originating marker by means of multicontact relays of a marker connector circuit.

Before proceeding further it is desirable to mention several other functions of the two common control circuits used for setting up this part of the connection.

1. The control circuits signal to the sender the class of the calling line, that is, for example, whether the line is a coin line or a noncoin line.

2. The sender-link control circuit signals to the sender the number of the district-link switch frame on which the selected district junctor appears, since this identification will be used later in the establishment of the connection.

3. The sender-link control circuit tests the circuit paths chosen from the line circuit to the sender before disconnecting from the connection, in order to insure the proper establishment of the connection. In case of a failure the control circuits will make repeated trials to establish the connection over different paths and give an alarm to the maintenance force.

4. Emergency control circuits are provided for use in case the regular control circuits are removed from service for maintenance reasons.

The next stage in the progress of the call is illustrated in figure 12. In this stage of the call the principal control unit is the originating marker. Its major function is to control the switches in the establishment of the connection to an idle outgoing trunk circuit to the called office, which may terminate in a distant office or in the same office as the calling subscriber.

When the subscriber sender connects to the originating marker through the connector circuit, the sender transfers the called-office code indication and the district link frame identification to the

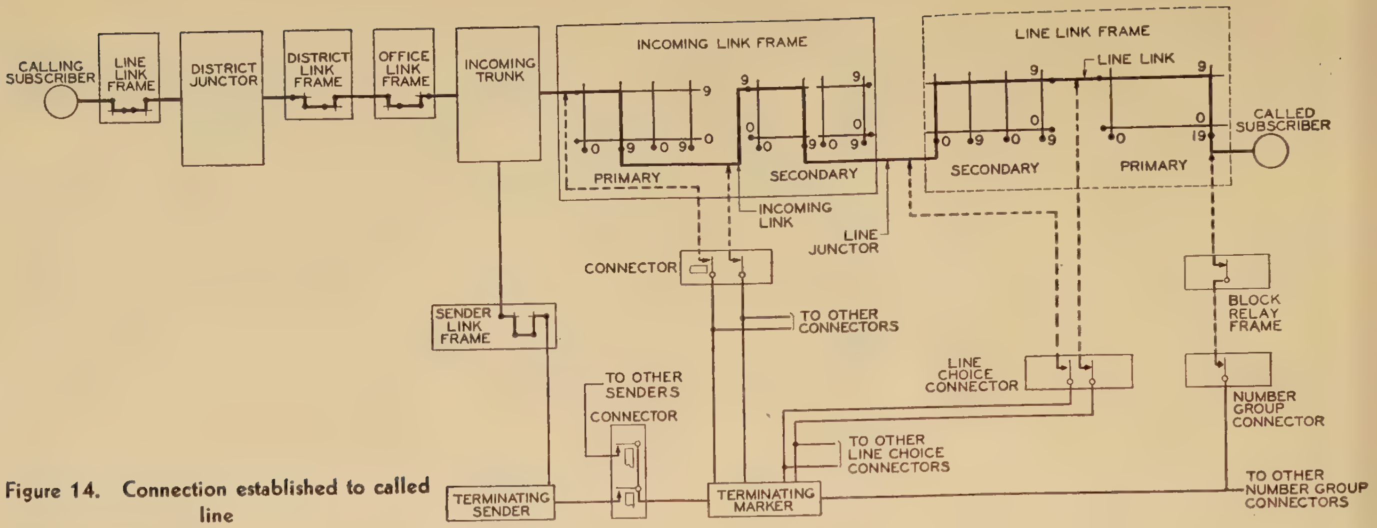


**Figure 14. Connection established to called line**

marker circuit. The called-office code indication causes the operation of a "route" relay in the marker corresponding to the particular office called.

There are a number of route relays in each marker and one is assigned to each called office routing. The route relay is connected as required by the office code to which it is assigned, so that it will direct the marker to the trunks of the called office and to the office-link switch frame on which these trunks appear and indicate the number of trunks in the group. The route relay also is connected to determine the type of the called office, such as crossbar, panel, or manual, and to set up the corresponding circuit conditions in the subscriber sender to enable the sender to handle the connection properly after the marker has been released. The connections of the route-relay contacts to the control relays in the marker are made flexible so as to permit the assignment of any route relay to any office code and to permit changes to be made from time to time in the route information, changes in trunk group sizes and location, changes in the type of terminating office, etc. The route relays and associated flexible connection facilities represent a considerable portion of the marker equipment, especially in large metropolitan offices where several hundred central offices are involved.

When the route relay is operated, the marker proceeds with the establishment of the connection as follows:

1. It connects to the office-link frame on which the trunks to the called office appear. This connection is made through the office-link frame connector circuit, one of which is provided for each office-link frame. Through this connector the marker is extended to the test leads of any desired trunk group on the office-link frame and to the crossbar switches of the frame. When so connected the marker has exclusive control of the trunks and switches of the frame and other markers which desire connection to the same frame are deprived of access until the connected marker releases.

2. The marker next tests the outgoing trunks to the called office and selects an idle one. If, as determined from the route relay, the trunks are divided over more than one frame, the marker will connect to the second group of trunks on the second office-link frame in case the first group of trunks is found to be busy.

3. The marker also connects by means of a connector circuit to the district-link frame associated with the district junctor to which the calling line is connected. The identification of this frame was obtained from the sender and the sender-link control circuit as previously mentioned. Through the connector circuit of the district-link frame the marker is extended to the control leads of the district junctor circuit and the crossbar switches of the district-link frame. As in the case of the office-link frame, only one marker is connected to a frame at a time.

4. The marker after selecting an idle trunk circuit which appears in a horizontal circuit path on one of the secondary switches of the office-link frame, then proceeds with the selection of an idle channel through the switches of the two switch frames. A number of these connecting channels is provided between the district junctor and the outgoing trunk. Each channel consists of a "district link" on the district-link frame, of an "office link" on the office-link frame, and an "office junctor" connecting the district-link frame to the office-link frame. The marker tests a group of these channels simultaneously and selects an idle one. It then operates the switch magnets which will connect these three paths of a channel, and the district junctor and the outgoing trunk together, thereby establishing a connection from the district junctor to the outgoing trunk.

5. When the marker has completed this operation it checks the connection to insure that it has been properly established and that it is capable of being held under control of the district junctor, before releasing itself from the connection.

6. The marker performs these functions in approximately 0.5 second then releases and becomes available for use on other calls.

It will be observed that the three links involved in establishing the connections between the district junctors and the outgoing trunks are used in series and are chosen simultaneously. Generally in other systems the establishment of a connection involving three such paths, is made in three successive stages with a possibility that after a selection has been made at one stage it will be found that the paths accessible to it are all busy and, therefore, the connection cannot be completed.

Before describing the next stage in the establishment of a call, it is desirable to point out other features and functions of the originating marker.

1. The marker permits wide variations in the sizes of trunk groups, permitting trunk groups as small as two and as large groups as may be required. This makes for an efficient use of the office-link frame terminals and thereby tends to reduce the office-link frame equipment.

2. The marker makes a second trial to establish connections over alternate trunk routes in case calls cannot be completed over the normally used groups because of busy conditions.

3. The marker makes a continuity test of the circuits over which the switches are controlled and tests them for short circuits, crosses, and open and grounded circuits which would interfere with the proper establishment of a call and where troubles are detected, it signals this condition to a common "trouble indicator" where an indication of the trouble and its location is recorded and a maintenance alarm given. The call is then completed over another group of circuits.

The first stage in the progress of the call through the terminating end of a crossbar office is illustrated in figure 13. It consists of connecting the incoming end of the selected trunk to a terminating sender for the purpose of receiving the number of the called line from the subscriber sender.

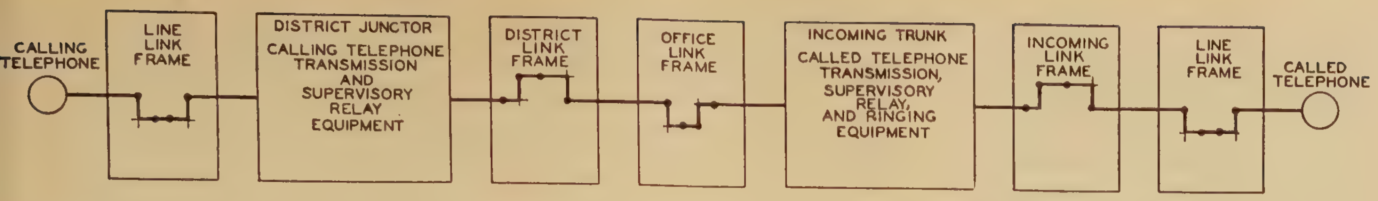


**Figure 15. Completed talking connection**

When the incoming trunk is selected by the originating end of the office equipment, the "sender link control" circuit associated with the terminating sender-link frame on which the incoming trunk appears, is called into action. The control circuit then proceeds with the following functions:

1. To locate the incoming trunk circuit, which appears on one of the ten horizontal paths of a primary switch.

2. It selects an idle sender link between this primary switch and a secondary switch on which there is an idle terminating sender.

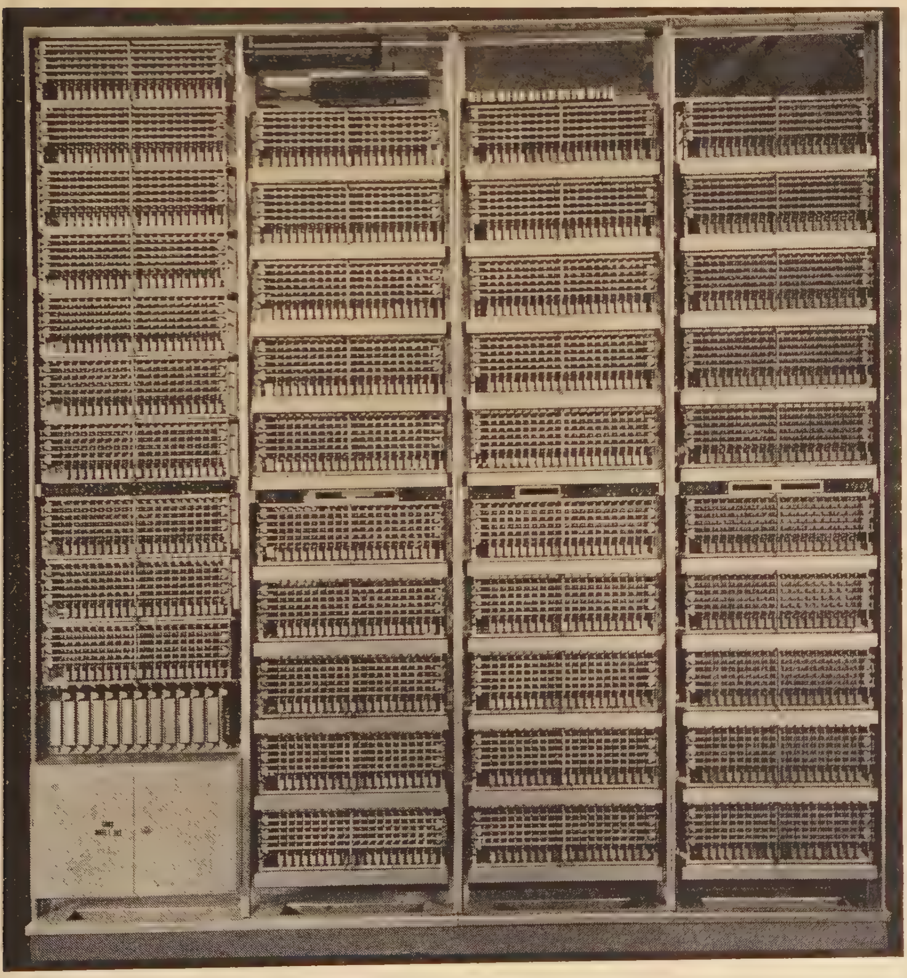
3. The control circuit selects one of the idle terminating senders reached through the secondary switch and then operates the selecting and holding magnets associated with the selected circuits, which will establish the connection from the incoming trunk to the terminating sender.

4. The control circuit will signal to the terminating sender the number of the incoming-link frame in which the incoming trunk appears. This frame identification will be used later in establishing the connection to the called line.

5. The control circuit will then disconnect after checking to insure that the connection to the sender has been properly established and that it will be held under control of the trunk and sender circuits after the control circuit leaves the connection.

As soon as this operation has been completed, which takes but a fraction of a second, the terminating sender will be in direct connection with the subscriber sender in the originating end of the connection. This path may be traced, by referring to figure 13, from the subscriber sender through the sender-link frame, through the district junctor, through the district-link and office-link frames, over the outgoing trunk to the incoming trunk, and through the terminating sender-link frame to the terminating sender.

**Figure 16. Line-link frame**



At this stage of the connection the calling subscriber is still connected with the subscriber sender, and dialing may be still in progress. As the subscriber proceeds with the dialing of the digits of the called number, the subscriber sender will transfer them to the terminating sender. This is done by means of impulses transmitted over the circuit paths between the two senders. When the subscriber sender has completed the transfer of the called number to the terminating sender, the subscriber sender will be released and the calling line will then be connected through the district junctor to the incoming trunk.

When the terminating sender has secured the record of the called line number, the sender then connects to an idle terminating marker by means of multicontact relays of a connector circuit.

The next stage in the progress of the call is shown in figure 14. The terminating marker is the principal control unit at this point in the connection. Its principal function is to provide means for establishing the connection from the incoming trunk to the called subscriber line.

When the terminating sender has connected to the terminating marker, the sender will transfer both the called line number and the incoming-link frame identification to the marker. The terminating marker then proceeds to establish the connection to the called line as follows:

1. It connects itself to the particular "number group connector" circuit including the "block relay" frame in which the called line appears in its numerical sequence. All subscriber lines are provided with a set of three test terminals which appear on the block-relay frame. These terminals correspond to the directory number of the subscriber line. A number group connector generally has access to the test terminals of several hundred line numbers depending on the terminating traffic to the lines.

2. The marker will obtain a connection through the number group connector to the busy-test terminal of the particular called line and determine whether the line is busy or idle.

3. It will determine from the two other test terminals, the identification of the

line-link frame where the called line appears, and the horizontal group of line links which has access to the called line. In addition, it determines the type of ringing to be applied to the called line from the circuit conditions on the test terminal.

4. Assuming that the called line is idle, the marker will connect, through the line-choice connector circuit, to the line-link frame and to the ten line links which have access to the called line.

5. It will then connect, through the connector circuit, to the incoming-link frame associated with the incoming trunk to which the calling subscriber line is now connected. The incoming-link frame identification was obtained from the sender-link control circuit through the sender as previously mentioned.

6. The marker will then select an idle channel through the incoming-link and line-link frames as previously described. This channel will consist of an "incoming link," a "line junctor," and a "line link" all to be connected in series. The marker then operates the proper selecting and holding magnets of the crossbar switches in each frame which establishes the connection from the incoming trunk to the called subscriber line.

7. The marker will then cause the incoming trunk to start the proper ringing over the called subscriber line and to transmit the ringing-tone signal over the trunk to the calling subscriber.

8. At this point the terminating marker and the terminating sender will have completed their functions and, together with the terminating sender-link frame, will be released. The complete connection will then be established from the calling line to the called line and the conversational circuit completed when the called subscriber answers.

If the terminating marker finds the called line busy it will cause the incoming trunk circuit to transmit a busy tone to the called subscriber.

The terminating marker has the following other important functions:

1. If the call is for a private branch exchange (*PBX*) the condition on one of the test terminals of the called line in the number group connector will inform the marker that the line is one of a group of lines. The marker will test all of the lines in the group, testing up to as many as 20 simultaneously, and will select an idle one. The lines of a private branch exchange may be assigned to nonconsecutive numbers within the usual 10,000 series, and with the exception of the numbers dialed, they may be assigned to line numbers in a special group of 2,500 outside of the 10,000 series. These features reduce the necessity for number changes due to the growth of private branch exchanges, and conserve subscriber line numbers in the office. The lines of a private branch exchange group can be distributed over several line-link frames and over two number-group connectors to equalize the terminating traffic load in the case of busy private branch exchanges.

2. The marker recognizes numbers dialed which are unassigned, disconnected, or changed numbers, and automatically routes such calls to an operator who will inform the calling subscribers as to the status of the numbers called.

3. In case the called number is on a party line, the marker determines from one of the test terminals which station of the line is to be rung, and signals the incoming trunk to provide the proper ringing.

4. The marker tests the continuity of the circuit paths to be used to the called line before establishing the connection, to insure that the connection is properly set up and that it will be held under control of the subscriber telephone after the marker disconnects. The marker also tests for short circuits, crosses, and grounds, and in case of a failure due to any inoperative condition it will connect itself to the common trouble indicator and leave a record of the trouble and its location and give an alarm to the maintenance force.

Figure 15 shows the complete talking connection through the various trunks and switch frames as finally established after all of the common control circuits have been released.

On a call to a subscriber served by a panel dial office, the connection is

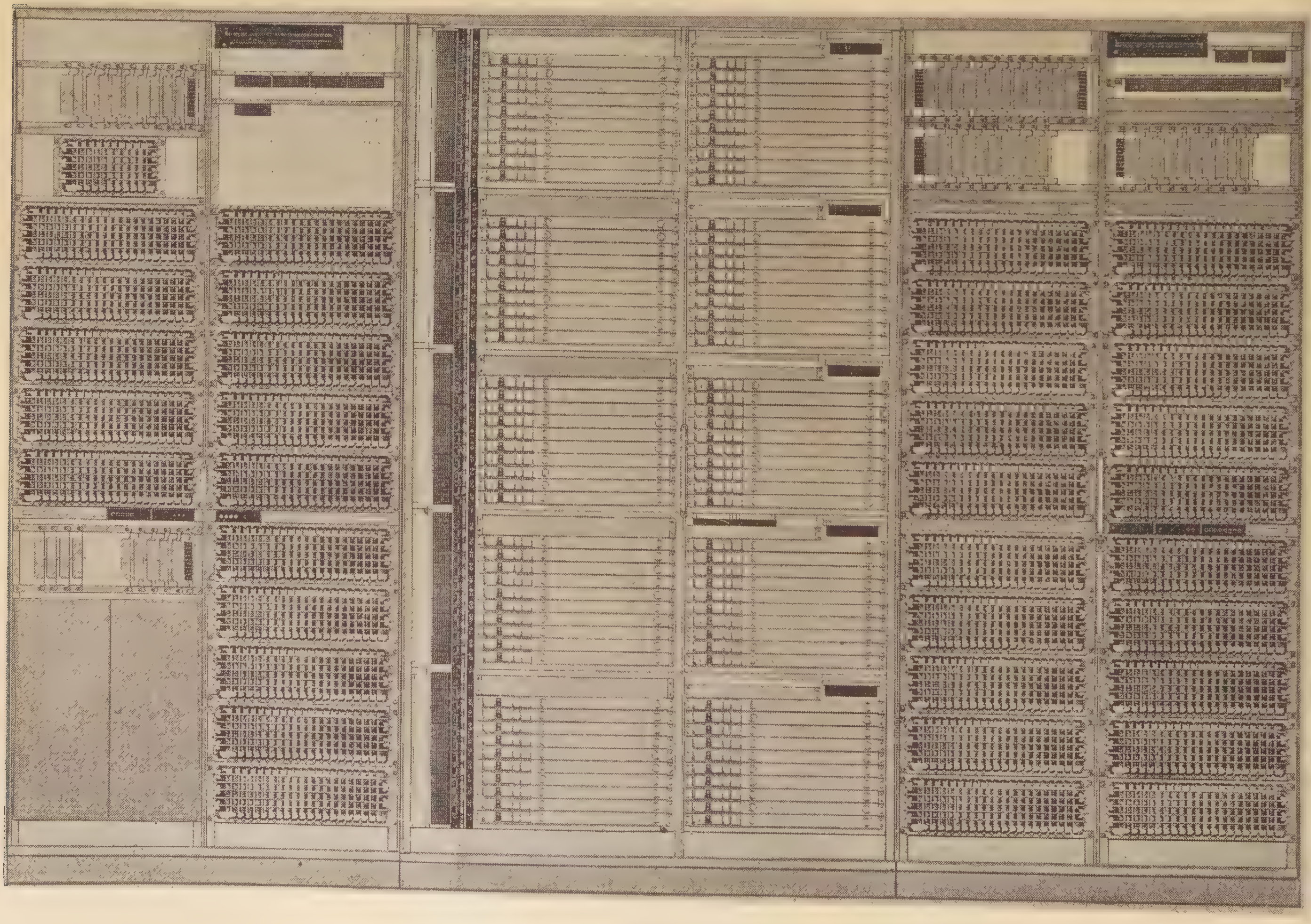


**Figure 17.** Three frame assembly of district-junctor, district-link, and sender-link frames

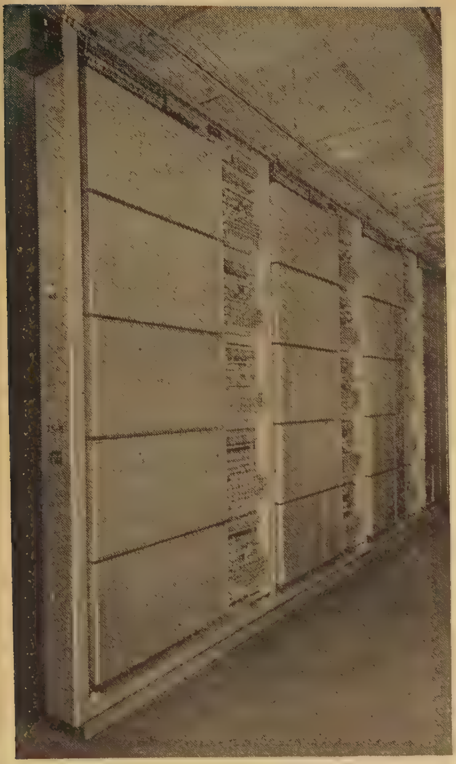


Figure 18. Sender frames

routed through the district-link and the office-link frames in the same manner as on a call terminating in a crossbar office, but in this case the idle trunk chosen on the office-link frame terminates in an incoming panel switch in the distant panel dial office. The subscriber sender of the crossbar office causes the incoming and final selectors in the terminating panel office to select the called subscriber line without the aid of any terminating senders in either office. When the subscriber sender has completed these functions it will be released and the connection will be established from the calling line over the interoffice trunk circuit and through the terminating panel incoming and final selectors to the called line. On this type of call the subscriber sender operates in the same manner as though the called line were in a crossbar office, and the selectors in the panel office operate in the same manner as though the call had originated in another panel office. No changes are required in the panel selectors to function with the crossbar office.

On a call for a subscriber in a manual office, the call would be routed through the switches of the district-link and the office-link frames as previously described and connected to a trunk circuit on the office-link frame which terminates in the *B* switchboard in the manual office. The subscriber sender of the crossbar office then transfers the called number by impulses transmitted over the interoffice trunk circuit to the operator's position equipment in the manual office. The called number appears in the form of visible numbers on the operator's keyshelf. The operator completes the connection by "plugging" the associated trunk circuit, which terminates on a cord and plug, into the called subscriber line jack.

A call originating in a panel dial office for a subscriber line in a crossbar office reaches the crossbar office through an incoming trunk circuit as in the case where the call originated in a crossbar office. The call from the panel office is then handled by the crossbar office terminating sender and marker in exactly the same manner as described for calls originating in the same crossbar office.

A call originating in a manual office for a line connected to the crossbar office reaches the crossbar office over an incoming trunk circuit from an *A* operator's position in the manual office. These incoming trunks in the crossbar office are similar to the incoming trunks previously described. In this case, however, the incoming trunk is connected to a terminating *B* sender and by means of this sender to a *B* board operator in the crossbar office. The *B* operator will obtain the called number verbally from the distant *A* operator and then, by means of the keyset on her position, register the called number in the terminating sender. The terminating sender will then select a terminating marker and the connection will be established in exactly the same manner as described for a call originating in a crossbar office.

### MAINTENANCE FACILITIES

Automatic routine testing circuits are provided for testing all the principal circuit units, such as the district junctors, incoming trunks, and senders. These test circuits automatically put each circuit, one after the other, through all of its functions on all classes of calls to insure that it performs satisfactorily. It tests the important relays of the circuits to insure that they have the proper adjustment to handle the worst circuit conditions. In case any circuit fails to meet the test conditions, the test is stopped and an alarm given to the maintenance force.

Trouble indicator circuits are provided for use in connection with the test and maintenance of the marker circuits. These circuits are arranged so that when trouble is encountered by a marker, the marker will seize the trouble indicator and operate combinations of relays and light small lamps which indicate the nature and the location of the failure and give an alarm to the maintenance force.

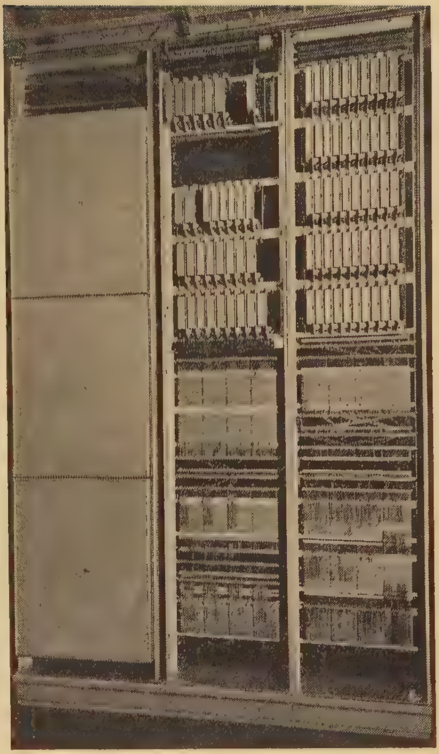


Figure 19. Originating marker frame

### Equipment

Figure 16 shows a typical switch frame used in the crossbar system. This particular frame is a "line link" frame which serves a group of subscribers for both originating and terminating traffic. The frameworks on which the equipment is mounted are constructed of rolled bulb angle-iron sections with a sheet-metal base. The bulb angle construction provides a framework which is light in weight and has the required strength, and permits an equipment mounting arrangement which conserves space and facilitates the wiring of the apparatus. The frames are welded and incorporate such features as sanitary base construction, guards to protect the apparatus and wiring against damage from the rolling ladders located between the rows of frames, and a cable duct or runway for the a-c power service cables with plug receptacle outlets for use with electric soldering irons, portable lights, etc.

These frame equipments are built in standardized units, which provide the required flexibility to satisfy the variations in telephone traffic and classes of service encountered in the different telephone areas. Where it has been necessary to divide an equipment assembly into several units, due to the limitations of handling, shipping, and to care for different classes of service, the equipments have been designed so that the installation effort required for interconnecting such units has been reduced to a minimum.

The bays of equipment located at the right, in figure 16, equipped with crossbar switches, are the primary line-link bays. The vertical units of these crossbar switches are wired to the subscriber lines. These primary bays are made available in units of 100 and 200 line capacities. As discussed previously the number of primary bays provided in a line-link frame may be varied to fit the traffic load of the subscriber lines. The left-hand bay of this frame contains the vertical file of crossbar switches, known as the secondary switches and the vertical units of these switches are wired to district junctors and line junctors. The line-link control circuit apparatus, which is common to the frame, is located at the bottom of this bay.

Figure 17 shows a group of three frame units, namely, the subscriber sender link, the district junctor, and the district-link frames, which are closely associated in the trunking network and have been designed as a fixed equipment group. However, for shipping reasons the group is divided into three separate equipment units. The district-junctor circuits, consisting primarily of relays, are mounted in groups on the middle frame. These groups are provided in standardized units of various types, such as those required to serve coin and noncoin subscriber lines. A similar arrangement of frames is used for the combination of terminating sender link, the incoming trunk, and the incoming-link frames.

Figure 18 shows a row of subscriber sender frames and a frame of *A* operator senders located at the extreme right. These frames accommodate five senders which may be of one type, or a combination of both types. The crossbar switch shown on the right of each subscriber sender unit, is a part of the sender circuit and is employed for the purpose of registering the called numbers dialed by the subscribers. The *A* operator senders are associated with the *A* operator switchboard equipment and are used for the completion of certain classes of calls such as toll and assistance calls.

A view of the originating marker frame is shown in figure 19. There will be a variation in the equipment on this frame for different cities due to the variation in the number of route relays required, the number depending upon the number of central-office codes that may be dialed by subscribers and operators. This variable feature is cared for by providing the route relay equipment in bays of 100 codes as shown in the right-hand bay. The terminal fields shown below the route relays on the frame provide the flexible connecting facilities which permit the use of any route relay for any office code and which readily permit changes in routings, variations in trunk group sizes, and other features which are subject to change from time to time.

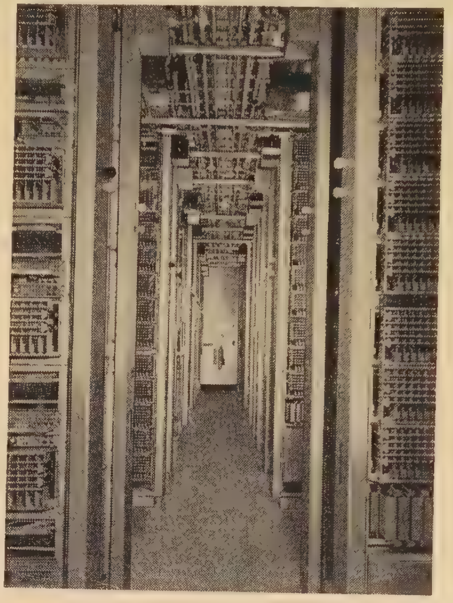


**Figure 20. Battery supply feeders, power wiring, fusing, etc.**

The power-plant equipment provided for the crossbar offices is similar to the equipment now being furnished for all large dial central offices. The principal power supply arrangements provide 48-volt direct current for the operation of practically all the signaling and the telephone transmission circuits. Also several other sources of direct current are provided for miscellaneous purposes as in other standard dial systems. A new distribution scheme for the battery feeders on the frames is employed which reduces the amount of copper required. A common set of 48-volt battery feeders supplies the signaling and talking current for all frames. Individual frame filters are connected across the battery supply leads at the frames where a noise-free battery supply is required for talking circuits. Figure 20 shows a view of the overhead battery cables, conduits for the a-c power leads, and the fuse cabinets for the fusing of the battery supply to a row of frames.

### APPLICATION

As mentioned in the first part of this paper, two crossbar dial central offices were cut into service in 1938 and these have now been in commercial operation for several months. One of these offices serves a residential area in Brooklyn, while the other serves a congested business area in the midtown Manhattan district of New York City. The operation of these offices under actual service conditions has been highly satisfactory and our expectations in regard to performance have been fully realized.

This type of system will be used for new offices in large cities instead of the panel system as rapidly as manufacturing and plant conditions permit and the apparatus which was designed for this system will be used in other fields of the telephone system.

# Breakdown Studies in Compressed Gases

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THE superior dielectric strength of compressed gases, their low dielectric loss, their low dielectric constant, their low cost, and the fact that they are self-healing make them very promising insulating media. Compressed-gas insulation has been used in precision condensers where low dielectric loss is essential; it has been tried in other types of equipment such as transformers; it has been suggested for electric power cables where the low dielectric constant is of considerable importance; and recently it has found interesting and important application in the production of very high voltages by electrostatic means for use in X ray and nuclear physics work.

While several investigations of the insulating properties of compressed gases have been made, nearly all of them have dealt with small total voltages and were made under conditions very different from those that would obtain in a practical application. The present work outlines the scope of former studies, gives an introduction to the physics of breakdown in gases, and presents experimental data for gas pressures, principally air, up to 600 pounds per square inch and direct voltages up to 450,000 volts. The results have been analyzed in the light of existing theories, and new evidence is presented to support the modifications in theory that are suggested.

## Experimental Aspects

Spark-over or breakdown between a pair of electrodes immersed in a gas will occur at a voltage which is, at ordinary temperatures, determined primarily by the gas pressure, the electrode separation, the electrode configuration, the nature of the gas, and the nature of the applied voltage, particularly its rate of increase.

The effect of pressure and electrode separation on the sparking voltage is given by Paschen's law,* which states that for a given gas and a uniform field the sparking voltage is a function of the product of the electrode separation and the pressure; the more general similarity law holds for electrodes which give nonuniform fields.

The curve in figure 1 shows the relationship between the sparking voltage for air and the product of the pressure and the electrode separation. The minimum exhibited by the curve may be considered to separate the region of vacuum breakdown from that of pressure breakdown. It will be observed that no uniform air gap can have a sparking voltage less than 350 volts. In the region of pressure breakdown the sparking voltage rises steadily as the product of the pressure and the electrode separation is increased.

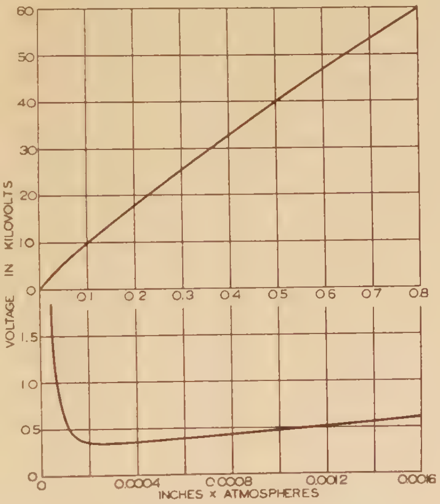

**Figure 1. Breakdown voltages for air—the Paschen relationship (from Schumann[45])**

Since pressures below atmospheric were used in the experiments which led to the formulation of Paschen's law, the curve in figure 1 has to be restricted with regard to pressure. The numerous tests which have been made at higher pressures, summarized in table I, have shown that data for pressures above a certain value, possibly ten atmospheres, cannot be represented by a single curve.

As figure 1 shows, large sparking voltages occur only when the product of pressure and electrode separation is large. Table I shows that in this region only a few measurements have been made, and they are for alternating voltages. The present work is aimed in the same direction but with direct potentials which, of course, permit a study of the effect of polarity.

With one exception the measurements presented in this paper have been made in air with gauge pressures up to 600 pounds per square inch and voltages up to a maximum of 450,000 volts. These studies have been made with uniform fields, needle point to plane, and concentric-cylinder electrode arrangements.

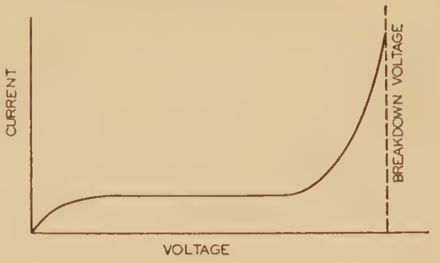

**Figure 2. Current flow before the initial discharge**

Uniform fields were used because they are of general interest and they permit a proper comparison with the results of others. The needle-point-to-plane arrangement was selected in order to determine the effect of pressure on the current-voltage characteristic of such points. This information is of interest to those operating Van de Graaff generators in compressed air. The cylindrical electrodes are also of general interest. Only cylindrical arrangements having a ratio of cylinder diameters approximately equal to $\epsilon$ were used. This ratio produces, for a given outside diameter of cylinder and a fixed voltage between cylinders, the smallest gradient at the surface of the inner conductor.

The current flowing through the gas prior to sparking was studied for the uniform fields and the cylinders as well as for the point-to-plane configuration. This feature of the work, measurement of current above atmospheric pressure, has not been reported by other workers in this field.

## Theoretical Background

In order to introduce the theoretical side of the breakdown picture, let the current-voltage characteristic for a pair of plane electrodes be considered. Figure 2 shows that the current first rises in proportion to the voltage at low voltages, then reaches a constant or saturation value (perhaps $10^{-12}$ amperes with the equipment used in the present experi-

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* In reality W. S. Harris[24] discovered the Paschen relationship in 1834, more than a half century before Paschen's publication. This is the more remarkable because absolute potential measurements could not be made until 1860. Harris therefore states his results in terms of the charge on a condenser of fixed capacity; for this case charge and voltage are proportional.

ments and maximum pressure), and later increases rapidly as the breakdown voltage is approached. When this limiting voltage is reached a new equilibrium condition is set up which is determined by the experimental system, but which is characterized by much larger values of current. The new equilibrium condition may be a glow (or some related discharge such as a brush or corona) or it may be an arc. In cases where the glow appears first an arc will appear at a still higher voltage. In the discussion that follows the term initial discharge is used to designate the first discharge that appears, and the voltage at which this occurs is called the ignition voltage or the initial voltage. The term breakdown voltage is used synonymously with sparking voltage to designate the voltage at which the initial discharge transfers to an arc.

**Table I. Index to Former Studies of Breakdown at Pressures Above Atmospheric**

| Name | Reference | Year | Maximum Pressure (Atmospheres) | Maximum Pressure for Maximum Spacing | Range of Spacing | Maximum Spacing for Maximum Pressure | Maximum Potential (Kilovolts) | Nature of Potential | Gas | Electrodes |
|---|---|---|---|---|---|---|---|---|---|---|
| Wolf | 50 | 1889 | 5 | 5 | 1 mm. | 1 mm. | 19 | d-c | Air, $O_2$, $N_2$, $CO_2$ | Spherical segments (10 cm. diameter) |
| Wolf | 50 | 1889 | 9 | 9 | 1 mm. | 1 mm. | 19 | d-c | $H_2$ | Spherical segments (10 cm. diameter) |
| Hemptinne | 26 | 1902 | 60 | 60 | (*a*) | (*a*) | 5.6 max | a-c | $N_2$ | Platinum wires (0.2 mm. diameter) |
| Hemptinne | 26 | 1902 | 50 | 50 | (*a*) | (*a*) | 6.4 max | a-c | $CO_2$, $O_2$ | Platinum wires (0.2 mm. diameter) |
| Hemptinne | 26 | 1902 | 80 | 80 | (*a*) | (*a*) | 4.6 max | a-c | $H_2$ | Platinum wires (0.2 mm. diameter) |
| Ryan | 44 | 1904 | 100 | 100 | 0.156–0.25 in. | 0.25 in. | 50 max | a-c | Air | Sewing needles (point-point) |
| Ryan | 44 | 1904 | 62 | 62 | 0.08 –0.25 in. | 0.25 in. | 58 max | a-c | $CO_2$ | Sewing needles (point-point) |
| Ekern | 6 | 1904 | 102 | 102 | 0.1–0.3 in. | 0.3 in. | 43 max | a-c | Air | Sewing needles (point-point) |
| Ekern | 6 | 1904 | 42 | 42 | 0.2 in. | 0.2 in. | 50 max | a-c | Air | Various kinds of points |
| Ryan | 42 | 1905 | 49 | 49 | 0.096 in. | 0.096 in. | 110 max | a-c | $CO_2$ | Aluminum wires (0.09375 in. diameter) rounded ends |
| Guye and Guye | 15 | 1905 | 86 | 86 | ~0.2 mm. | ~0.2 mm. | 19 | d-c | Air, $N_2$, $O_2$ | Platinum wires (1 mm. diameter) |
| Guye and Guye | 15 | 1905 | 63 | 63 | ~0.2 mm. | ~0.2 mm. | 12 | d-c | $H_2$ | Platinum wires (1 mm. diameter) |
| Guye and Guye | 15 | 1905 | 53 | 53 | ~0.2 mm. | ~0.2 mm. | 19 | d-c | $CO_2$ | Platinum wires (1 mm. diameter) |
| Fessenden | 10 | 1905 | 12 | 12 | 0.083 in. | 0.083 in. | 40 max | a-c | Air | Flat plate condenser. [First application of compressed gas.] |
| Cassuto and Occhialini | 3 | 1907 | 102 | 1.6 | 0.1–6.3 mm. | 0.1 mm. | (*b*) | d-c | Air | Planes (4 cm. diameter) |
| Ceruti | 4 | 1909 | 40 | 25 | 0.03–0.22 mm. | 0.156 mm. | 13.5 | d-c | Air | Gold plated spheres (15 mm. diameter) |
| Ceruti | 4 | 1909 | 50 | 30 | 0.03–0.22 mm. | 0.125 mm. | 24.6 | d-c | Air | Platinum plated spheres (15 mm. diameter) |
| Watson | 48 | 1909 | 15 | 15 | (*c*) | (*c*) | (*c*) | d-c | Air | Spheres (0.3175, 0.635, 2.54 cm. diameter) |
| Wien | 49 | 1909 | 21 | 21 | 3 mm. | 3 mm. | 48 max | a-c | Air, $CO_2$ | Condenser (5 concentric cylindrical plates) |
| Hayashi | 25 | 1914 | 70 | 70 | 0.52–1.82 mm. | 1.82 mm. | 117 | d-c | Air, $N_2$ | Magnesium spheres (1 cm. diameter) |
| Hayashi | 25 | 1914 | 70 | 60 | 0.52–1.82 mm. | 1.08 mm. | 110 | d-c | $CO_2$ | Magnesium spheres (1 cm. diameter) |
| Hayashi | 25 | 1914 | 30 | 30 | 0.58 mm. | 0.58 mm. | 41 | d-c | $N_2$ and $H_2$ mixed | Gold spheres (1 cm. diameter) |
| Hayashi | 25 | 1914 | 70 | 70 | 0.65 mm. | 0.65 mm. | 70 | d-c | (*d*) | Gold spheres (1 cm. diameter) |
| Guye and Stancescu | 19 | 1917 | 53 | 16 | 0.34–2.24 mm. | 0.34 mm. | 35 | d-c | $CO_2$ | Gold plates (14 mm. diameter) |
| Guye and Mercier | 16 | 1920 | 26 | 4.1 | 0.5–5 mm. | 0.5 mm. | 54 | d-c | $CO_2$ | Planes (45 mm. diameter) |
| Guye and Mercier | 16 | 1920 | 4.1 | 4.1 | 5 mm. | 5 mm. | 53 | d-c | $CO_2$ | Calottes (150 mm. radius of curvature) |
| Guye and Mercier | 16 | 1920 | 23.1 | 23.1 | 1 mm. | 1 mm. | 52 | d-c | $CO_2$ | Calottes (30 mm. radius of curvature) |
| Guye and Mercier | 16 | 1920 | 34.9 | 34.9 | 0.5 mm. | 0.5 mm. | 43 | d-c | $CO_2$ | Calottes (15 mm. radius of curvature) |
| Hammershaimb and Mercier | 23 | 1921 | 1* | 1 | 0.5–5 mm. | 5 mm. | 18 | d-c | $N_2$ | 13 sets of electrodes ranging from points to planes |
| Hammershaimb and Mercier | 23 | 1921 | 4* | 4 | 0.5–4.5 mm. | 4.5 mm. | 52 | d-c | $N_2$ | 9 sets of electrodes |
| Hammershaimb and Mercier | 23 | 1921 | 10* | 10 | 0.5–2.5 mm. | 2.5 mm. | 69 | d-c | $N_2$ | 8 sets of electrodes |
| Hammershaimb and Mercier | 23 | 1921 | 50 | 1 | 0.5–5 mm. | 0.5 mm. | 69 | d-c | $N_2$ | Spherical segments (15 mm. diameter) |
| Hammershaimb and Mercier | 23 | 1921 | 55 | 1 | 0.5–5 mm. | 0.5 mm. | 75 | d-c | $N_2$ | Planes (10 mm. diameter) |
| Hammershaimb and Mercier | 23 | 1921 | 50 | 1 | 0.5–5 mm. | 0.5 mm. | 80 | d-c | $N_2$ | Planes (45 mm. diameter) |
| Guye and Mercier | 17 | 1922 | 51 | 5.5 | 0.5–5 mm. | 0.5 mm. | 62 | d-c | $CO_2$ | Spherical segments (15 mm. diameter) |
| Hammershaimb | 22 | 1923 | 50 | 10 | 0.5–2.5 mm. | 0.5 mm. | 80 | d-c | $N_2$ | Spherical segments (15 mm. diameter) |
| Guye and Weigle | 20 | 1923 | 22 | 22 | 0.5 mm. | 0.5 mm. | 24 | d-c | $CO_2$ | Spherical segments (15 mm. diameter) |
| Guye and Weigle | 20 | 1923 | 43 | 23 | 0.5–1 mm. | 0.5 mm. | 54 | d-c | $CO_2$ | Spherical segments (15 mm. diameter) |
| Guye and Weigle | 20 | 1923 | 38 | 20 | 0.5–1 mm. | 0.5 mm. | 60 | d-c | $N_2$ | Spherical segments (15 mm. diameter) |
| Guye, Mercier, and Weigle | 18 | 1925 | 40 | 5 | 0.5–5 mm. | 0.5 mm. | 56 | d-c | $CO_2$ | Spherical segments (15 mm. diameter) |
| Palm | 34 | 1926 | 15 | 15 | 2–8 mm. | 8 mm. | 220 max | a-c | $N_2$ | Planes (108 mm. diameter) |
| Palm | 34 | 1926 | 15 | 15 | 2–8 mm. | 8 mm. | 255 max | a-c | $CO_2$ | Planes (108 mm. diameter) |
| Goodlet, Edwards, and Perry | 14 | 1930 | 5 | 5 | 0–10 cm. | 10 cm. | 100 eff | a-c | Air | Rods (1/2 in. diameter), rounded ends |
| Reher | 38 | 1931 | 26 | 2 | 1–18 mm. | 2 mm. | 110 eff | a-c | Air | Planes (about 5 to 8 in. diameter) |
| Reher | 38 | 1931 | 28 | 10 | 0.5–4 mm. | 2 mm. | 105 eff | a-c | Air | Spheres (16 mm. diameter) |
| Bölsterli | 1 | 1931 | 17* | 17 | 0–6 cm. | 6 cm. | 200 eff | a-c | $N_2$ | Needle gap |
| Bölsterli | 1 | 1931 | 20 | 20 | 3.2 mm. | 3.2 mm. | 60 eff | a-c | $N_2$, $CO_2$ | Concentric cylinders (25.4 and 31.8 mm. diameter) |
| Bölsterli | 1 | 1931 | 20 | 20 | 3.2 mm. | 3.2 mm. | 13 eff | a-c | He | Concentric cylinders (25.4 and 31.8 mm. diameter) |
| Zeier | 51 | 1932 | 116 | 5 | 0.1–5 mm. | 0.4 mm. | 100 | d-c | Air | Spheres (15 mm. diameter) |
| Zeier | 51 | 1932 | 48 | 5 | 0.2–5 mm. | 0.6 mm. | 80 | d-c | Air | Spherical segments (300 mm. diameter) |
| Zeier | 51 | 1932 | 48 | 48 | 0.3–0.5 mm. | 0.5 mm. | 70 | d-c | Air | Sphere (2 mm. diameter)—segment (300 mm. diameter) |

* = constant at value stated.

(*a*) Very small; not specified. (*b*) Arbitrary units. (*c*) Results show gradients as a function of pressure. (*d*) Air, $N_2$, $O_2$, $CO_2$, $H_2$, and illuminating gas.

To understand the behavior of the current it is necessary to know that normally cosmic rays, radioactive radiations, and photoelectric action are constantly producing ions and electrons in the gas, at the electrodes, and at the walls of the container if there are any. At low voltages the current is produced by the movement of these charge carriers, under the action of the electric field, to the electrodes. The saturation condition is reached when the charge carriers arrive at the electrodes at the same rate as that at which they are produced by the causes mentioned above, allowing of course for such effects as recombination. The current rises above the saturation value when the electric field is able to cause a multiplying of the charge carriers in the gas and at the electrodes. This multiplying action increases rapidly with

**Table I (Continued). Index to Former Studies of Breakdown at Pressures Above Atmospheric**

| Name | Reference | Year | Maximum Pressure (Atmospheres) | Maximum Pressure for Maximum Spacing | Range of Spacing | Maximum Spacing for Maximum Pressure | Maximum Potential (Kilovolts) | Nature of Potential | Gas | Electrodes |
|---|---|---|---|---|---|---|---|---|---|---|
| Zeier | 51 | 1932 | 116 | 5 | 0.2–4 mm. | 0.6 mm. | 80 | d-c | $N_2$ | Spheres (15 mm. diameter) |
| Zeier | 51 | 1932 | 48 | | | 0.8 mm. | 80 | d-c | $N_2$ | Spherical segments (300 mm. diameter) |
| Zeier | 51 | 1932 | 29 | | | 1.2 mm. | 80 | d-c | $N_2$ | Segment (300 mm. diameter)—plane |
| Zeier | 51 | 1932 | 48 | 48 | 0.3–0.5 mm. | 0.5 mm. | 58 | d-c | $N_2$ | Sphere (2 mm. diameter)—segment (300 mm. diameter) |
| Zeier | 51 | 1932 | 56.5 | 5 | 0.2–4 mm. | 0.6 mm. | 90 | d-c | $CO_2$ | Spheres (15 mm. diameter) |
| Zeier | 51 | 1932 | 48 | | | | 75 | d-c | $CO_2$ | Spherical segments (300 mm. diameter) |
| Zeier | 51 | 1932 | 48 | 5 | 0.1–~3 mm. | 0.6 mm. | 70 | d-c | $CO_2$ | Spheres (2 mm. diameter) |
| Zeier | 51 | 1932 | 39 | 39 | 0.5 mm. | 0.5 mm. | 58 | d-c | Air and $N_2$ mixed | Spheres (15 mm. diameter) |
| Palm | 33 | 1934 | 25 | 14 | 1–16 mm. | 1 mm. | 280 max | a-c | $N_2$ | Planes (108 mm. diameter) |
| Palm | 33 | 1934 | 23 | 18 | 1–8 mm. | 1 mm. | 290 max | a-c | $CO_2$ | Planes (108 mm. diameter) |
| Palm | 33 | 1934 | 10* | 10 | 6.5 mm. | 6.5 mm. | 375 max | a-c | $N_2$ | Concentric cylinders (38 and 51 mm. diameter) |
| Palm | 33 | 1934 | 15.7* | 15.7 | 18.5 mm. | 18.5 mm. | 445 max | a-c | $N_2$ | Concentric cylinders (133 and 170 mm. diameter) |
| Palm | 33 | 1934 | 14* | 14 | 23.5 mm. | 23.5 mm. | 556 max | a-c | $N_2$ | Concentric cylinders (150 and 197 mm. diameter) |
| Palm | 33 | 1934 | 14* | 14 | 6.4 mm. | 6.4 mm. | 228 max | a-c | $N_2$ | Concentric cylinders (25.4 and 31.8 mm. diameter) |
| Goldman and Wul | 12 | 1934 | 17 | 17 | 3–17.5 mm. | 17.5 mm. | 80 max | a-c | $N_2$ | Point (platinum wire 0.435 mm. diameter)—plane |
| Goldman and Wul | 12 | 1934 | 17 | 13 | 1–10 mm. | 5 mm. | 130 | d-c | $N_2$ | Negative point (platinum wire 0.435 mm. diameter)—plane |
| Goldman and Wul | 12 | 1934 | 17 | 17 | 1–50 mm. | 50 mm. | 150 | d-c | $N_2$ | Positive point (platinum wire 0.435 mm. diameter)—plane |
| Goldman and Wul | 12 | 1934 | 17 | 9 | 3.7–10 mm. | 3.7 mm. | 115 | (*e*) | $N_2$ | Positive point (platinum wire 0.435 mm. diameter)—plane |
| Goldman and Wul | 12 | 1934 | 17 | 6 | 3.7–10 mm. | 5 mm. | 160 | (*e*) | $N_2$ | Negative point (platinum wire 0.435 mm. diameter)—plane |
| Goldman and Wul | 13 | 1935 | 25 | 25 | 10 mm. | 10 mm. | 55 | d-c | $N_2$ | Positive point (platinum wire 0.435 mm. diameter)—plane |
| Goldman and Wul | 13 | 1935 | 25 | 25 | 10 mm. | 10 mm. | 130 | d-c | $N_2$ | Negative point (platinum wire 0.435 mm. diameter)—plane |
| Goldman and Wul | 13 | 1935 | 25 | 25 | 10 mm. | 10 mm. | 50 max | a-c | $N_2$ | Point (platinum wire 0.435 mm. diameter)—plane |
| Goldman and Wul | 13 | 1935 | 31 | 31 | 10 mm. | 10 mm. | 50 max | a-c | $N_2$ | Point-plane. Temperature = 13°C. |
| Goldman and Wul | 13 | 1935 | 31 | 31 | 10 mm. | 10 mm. | 36 max | a-c | $N_2$ | Point-plane. Temperature = 100°C. |
| Goldman and Wul | 13 | 1935 | Up to 48 | | Up to 20 mm. | | 150 | a-c and d-c | $N_2$ | Various odd shapes (all unsymmetrical gaps) |
| Finkelmann | 11 | 1937 | 20 | ~ 9 | 2–20 mm. | 7 mm. | 375 max | a-c | $N_2$ | Brass plates (13.5 cm. diameter) |
| Finkelmann | 11 | 1937 | 20 | ~ 7 | 1–20 mm. | 7 mm. | 375 max | a-c | $CO_2$ | Brass plates (13.5 cm. diameter) |
| Finkelmann | 11 | 1937 | 20 | ~ 8 | 1–20 mm. | 7 mm. | 400 max | a-c | Air | Brass plates (13.5 cm. diameter) |
| Finkelmann | 11 | 1937 | 20 | ~14 | 1–20 mm. | 10 mm. | 380 max | a-c | $H_2$ | Brass plates (13.5 cm. diameter) |
| Finkelmann | 11 | 1937 | 19 | 19 | 9.35 mm. | 9.35 mm. | 250 max | a-c | Air, $N_2$, $CO_2$ | Concentric cylinders (180 and 199.4 mm. diameter) |
| Finkelmann | 11 | 1937 | 21 | 21 | 9.35 mm. | 9.35 mm. | 165 max | a-c | $H_2$ | Concentric cylinders (180 and 199.4 mm. diameter) |
| Finkelmann | 11 | 1937 | 11 | 11 | 19.3 mm. | 19.3 mm. | 370 max | a-c | Air, $N_2$, $CO_2$ | Concentric cylinders (159.8 and 199.4 mm. diameter) |
| Finkelmann | 11 | 1937 | 16 | 16 | 19.3 mm. | 19.3 mm. | 360 max | a-c | $H_2$ | Concentric cylinders (159.8 and 199.4 mm. diameter) |
| Finkelmann | 11 | 1937 | 8 | 8 | 29 mm. | 29 mm. | 380 max | a-c | Air, $N_2$, $CO_2$ | Concentric cylinders (140.0 and 199.4 mm. diameter) |
| Finkelmann | 11 | 1937 | 13 | 13 | 29 mm. | 29 mm. | 375 max | a-c | $H_2$ | Concentric cylinders (140.0 and 199.4 mm. diameter) |
| Finkelmann | 11 | 1937 | 6 | 6 | 39.7 mm. | 39.7 mm. | 375 max | a-c | Air, $N_2$, $CO_2$ | Concentric cylinders (119.2 and 199.4 mm. diameter) |
| Finkelmann | 11 | 1937 | 10 | 10 | 39.7 mm. | 39.7 mm. | 365 max | a-c | $H_2$ | Concentric cylinders (119.2 and 199.4 mm. diameter) |
| Rodine and Herb | 40 | 1937 | 5 | 3 | 2–10 mm. | 5 mm. | 100 | d-c | (*f*) | Brass spheres (5 cm. diameter) |
| Hudson, Hoisington, and Royt | 29 | 1937 | 7 | 7 | 3 mm. | 3 mm. | 150 | d-c | (*g*) | Brass spheres (5 cm. diameter) |
| Hudson, Hoisington, and Royt | 29 | 1937 | 7 | 7 | 3 mm. | 3 mm. | 98 | d-c | (*h*) | Brass spheres (5 cm. diameter) |

* = constant at value stated.
(*e*) Impulse. (*f*) Various mixtures of $CCl_4$ and air. (*g*) Various mixtures of $CCl_2F_2$ and air. (*h*) Various mixtures of $SO_2$ and air.

voltage at voltages just below the ignition value. At the ignition voltage the current ceases to depend on external sources of ionization; it becomes self-sustaining.

A complete analysis of the problem involves accurate knowledge about all the possible methods of producing charge carriers either at the electrodes or in the gas, about the manner in which these carriers are moved through the gas as a result of diffusion and the influence of the electric field, and finally about the manner in which they may disappear. At the present time it is recognized that new carriers may be produced by a number of methods, but adequate quantitative knowledge about most of these is not yet available.

Plausible ionization processes in the gas are: (1) ionization by electron impact; (2) ionization by positive-ion impact; (3) photoelectric action; (4) ionization by metastable atoms and excited atoms; (5) multistage ionization (all types); (6) ionization by neutral atoms; (7) thermal ionization.

The anode need not be considered because electrons coming from it would immediately return. The possibility of the emission of positive ions from the anode appears remote and, so far, is not supported by experiment.

Clearly the difficulty is not one of finding a conceivable process by which the charge carriers can be multiplied, but rather one of finding which of the many available ones are important. There is general agreement that the action of electrons in the gas is the important or primary process. This is the $\alpha$ process. It assumes that one electron produces $\alpha$ new ion pairs in traveling one centimeter through the gas. Now if an electron leaves the cathode, new ones will be generated in geometrical progression, giving rise to an electron avalanche; the number of electrons in the avalanche is $\epsilon^{\int_0^d \alpha dx}$ after the distance $d$ to the anode has been traversed. Experimental tests have shown that the current rise just preceding the initial discharge cannot be accounted for by the $\alpha$ mechanism alone.

The $\beta$ mechanism assumes that the positive ions ionize neutral gas molecules as they move to the cathode and that one ion in moving one centimeter produces $\beta$ new ion pairs. On the assumption that only the $\alpha$ and $\beta$ processes are active, an equation may be derived which is able to describe the current rise before the initial discharge. The equation furthermore predicts an infinite current for a certain combination of the variables $\alpha$, $\beta$, and $d$, or for a certain combination of pressure, voltage, and electrode separation. The relationship of variables predicting unlimited current flow has been interpreted to be the condition necessary for the initial discharge, and has been found to be in agreement with experimental values. The self-sustaining current which accompanies the initial discharge is established when the ions produced by one electron are able to produce one electron.

An alternate possibility is the $\gamma$ mechanism which assumes that the positive ions liberate electrons when they strike the cathode, and that $\gamma$ electrons are emitted by each positive ion. This assumption with the $\alpha$ mechanism also allows the current before the initial discharge to be described and the ignition voltage to be predicted.

It happens that there are still other mechanisms which when taken with the $\alpha$ process will allow the predischarge current to be described and the initial voltage to be predicted. They are the action of photons in the gas or at the cathode, and the action of metastable atoms in the gas or at the cathode. The most generally accepted one is the $\eta$ mechanism which assumes that photons liberate electrons from the cathode and that $\eta$ electrons are liberated by each photon. Of course it is also possible to satisfy the current and voltage requirements with a combination of two or more of the secondary processes.

The multiple solution difficulty arises from the fact that, in all equations, $\alpha$ dictates the principal behavior of the current rise in that it governs exponentials whereas the other quantities play a less dominating role. The experimental data are not especially precise and do not permit a distinction to be made between the various equations.

From the standpoint of understanding the elementary physical processes that are at work, it is evident that little can be concluded from considering only the predischarge current rise and the initial voltage. Since it has already been mentioned that one of the features of the present work is the measurement of current above atmospheric pressure, it might at first seem that this is misdirected effort. However, the currents which can be described by the equations mentioned above are not the currents measured in this study; the currents measured here are self-sustaining values.

Additional information has been obtained from other sources, such as the time necessary to initiate the self-sustaining condition, photographs of the early stages of breakdown, direct experiments which study the individual elementary processes, and the experience with all the various types of gas discharges. The evidence seems to indicate that many of the proposed mechanisms are either absent or that they are too rare to consider in the ordinary sparking phenomenon. At present it is believed that the important ones for the common gases are the $\alpha$, $\gamma$, and $\eta$ processes, with the additional consideration of field distortion due to space charge. For long sparks in mixed gases such as lightning strokes, or for self-sustaining discharges from isolated electrodes, it appears that photo-ionization in the gas becomes important as well. Here it seems necessary to have the electrons regenerated in the gas rather than at the electrodes, as they are with the $\gamma$ and $\eta$ processes.

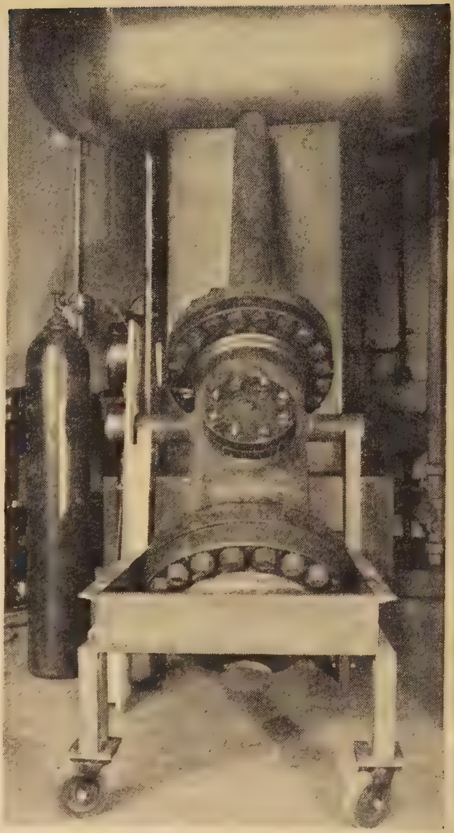

**Figure 3. Pressure vessel and generator**

To date the theory has been concerned principally with explaining breakdown at pressures which do not exceed atmospheric. At higher pressures one might expect to find new processes at work; a discussion of this possibility will be included with the results.

## Apparatus

The experiments presented in this paper were made in a special portable pressure vessel having an internal diameter of 13 inches and an inside length of 42 inches.

The tank was fabricated by welding together standard outside diameter pipe and steam fittings. It had two hand holes near the center and each contained a window. The tank was so suspended on its portable truck that all the operations, including assembly, could be managed readily by one person. Figure 3 shows the complete vessel and the generator in the operating position.

The high direct potentials (up to one-half million volts) as obtained from a Van de Graaff generator, were introduced into the pressure chamber through a solid Textolite bushing which was forced into a tapered nozzle at the upper end of the tank. The bushing extended 15 inches into the container and 65 inches outside.

The electrodes used for producing uniform fields were turned from ordinary cold-rolled steel. They had a flat section 2 inches in diameter and edges formed by using a constantly decreasing radius of curvature. The maximum diameter of each electrode was $7\,^{1}/_{16}$ inches. Figure 4 shows a sectional view of the three types of electrodes that were used. Experience showed that the distribution of sparks over the flat area was uniform and that the sparks were practically all confined to this area. For this reason it was assumed that the electrodes produced a satisfactory uniform field.

The low-potential electrode was supplied with a ball and socket joint which permitted the electrodes to be made perfectly parallel at any time simply by forcing them together. This electrode was moved by a fine screw which allowed the electrode separation to be known to within 0.001 inch. The technique used eliminated back lash, and stretching of the tank was readily corrected for by adjusting the scale. An ordinary spark plug was used as a bushing for leading the current through the tank wall; the leads both inside and outside the tank were shielded.

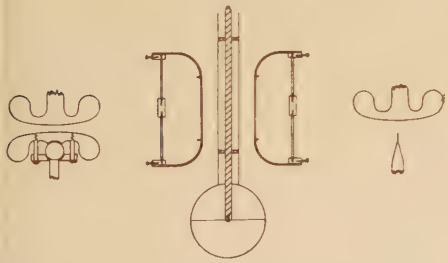

**Figure 4. Electrode configurations: uniform field, concentric cylinder, point to plane**

The needle-point-to-plane configuration was realized by replacing the low-potential electrode of the system described above with a 30-degree cone having a phonograph needle set in its point.

Copper was used for making the cylindrical electrodes for constructional reasons. In each case the inner electrode was attached to the conductor running through the bushing and terminated in an aluminum sphere which insured that the highest gradient would occur in the test section. The outer cylinders were held between spun flanges which were at ground potential, the cylinder was insulated from the flanges. The whole system was held in position by four adjustable screws directed radially against the tank wall from each flange. This allowed the cylinders to be made perfectly concentric. Experience showed that the distribution of sparks within the length of the outer cylinder was perfectly uniform and the insulating feature made it possible to measure the current flow to the outer cylinder.

Four sets of cylindrical electrodes were employed and each of these had a ratio of diameters as nearly equal to $\epsilon$ as it was possible to obtain them. The combinations of diameters used were $^{1}/_{2}$ inch and $1\,^{1}/_{16}$ inches; $^{3}/_{4}$ inch and $2\,^{1}/_{16}$ inches; $1\,^{1}/_{8}$ inches and 3 inches; and $1\,^{1}/_{2}$ inches and 4 inches. The outer cylinder was 5 inches long in all cases.

Gas was obtained in commercial tanks and was dried by passing it slowly through a five-foot tower filled with Drierite and then through phosphorus pentoxide. The moisture inevitably trapped in the vessel was removed by placing a container of phosphorus pentoxide in the tank and circulating the enclosed gas for a period of 10 or 12 hours. As the results will show, air was generally employed, though two tanks of nitrogen and one of helium were used in some special experiments.

The voltage measurements were made with a special resistor consisting of 960 10-megohm units connected in series and encased in a suitable Textolite container filled with insulating oil. A microammeter (accuracy one-half of one per cent) was used for measuring the resistor current. Numerous tests indicated that this voltage measuring system certainly gave an accuracy of two per cent, and probably of one per cent. The meter was used within a grounded case and was protected from surges by the usual system of a neon bulb and a suitable series resistance. The long lead to the resistor was completely shielded.

The current to the low-potential electrode was measured with a multiple-range semisuspension meter which was used in a grounded case with surge protection and shielded leads. Currents as small as 0.005 microampere were detectable with this instrument.

The pressure was measured with two Crosby steam gauges, one measuring pressures to 200 pounds and the other to 1,000 pounds.

The following simple and definite procedure was always followed in taking observations. The potential was increased in a step-wise fashion from a value definitely below the minimum voltage at which the gap would break down, until a spark was produced. The increments approximated one per cent or two per cent, and voltage was held constant for one minute at each step. The value at which breakdown occurred and also the current flowing just before breakdown were recorded. The procedure was repeated until about ten readings were available for averaging.

Although the technique employed is time consuming, it was felt that it produced the desired results. The readings of any one group sometimes differed from the average by as much as ten per cent, but the average was generally reproducible to within two to five per cent. The large amount of scattering occurred only at the higher pressures, where the time lag becomes excessively large; at low pressures, where the lag is small, the measurements can be taken a good deal faster and more accurately. Inasmuch as the breakdown generally consisted of a single spark, and this of short duration because of the small capacity of the generator, no trouble was experienced from the arc effect such as Reher[38] reports.

Some of the workers who have made measurements at high pressures have used ultraviolet radiation, X rays, or radioactive radiations on the cathode to cut down the time lag. Such devices were not used in this work, as it was desired to study the currents existing normally without added sources of ionization.

## Results

### Uniform Field

The results for the uniform field may well be introduced by considering figures 5 and 6. The first of these shows values of breakdown voltage as a function of electrode separation for various constant pressures. Clearly the voltage increases almost linearly with the separation at any pressure. Figure 6 shows the values of breakdown voltage as a function of pressure for various fixed separations. Here the voltage increases linearly with the pressure for the first eight or ten atmospheres and then more and more slowly as the pressure is raised still further. At 600 pounds the voltage is less than 60 per cent of what it would be if the linear rise had continued throughout the entire range. As other workers have observed at smaller spacings, the Paschen law does not apply above about ten atmospheres.

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[38] For all numbered references, see list at end of paper.

The above results were obtained from a single sample of carefully dried air. The measurements were repeated for three other samples of air, and it was found that the results are reproducible to within a few per cent when proper care and precautions are taken to have all essential conditions the same.

However, it is possible to get breakdown voltages widely different from those that have been presented. For example, by simply sanding the flat part of the electrodes the breakdown voltage at the higher pressures can be reduced by a factor of three or four. At the lower pressures the reduction is smaller, but even at one or two atmospheres it may be as much as 25 per cent for the first few sparks.

The detrimental effect of roughening the electrodes can be overcome by prolonged sparking. At low pressures the voltage rises rapidly with the first few sparks and quickly attains a maximum value. At higher pressures the maximum voltage is not attained until several hundred, or possibly thousands of sparks have passed. The beneficial result from sparking may be termed electrical conditioning of the electrodes and the measurements so far presented apply to completely conditioned electrodes. The results for such electrodes were found to be independent of the polarity of the generator or of the sample of air; they were the same when measurements were made with ascending or descending pressures.

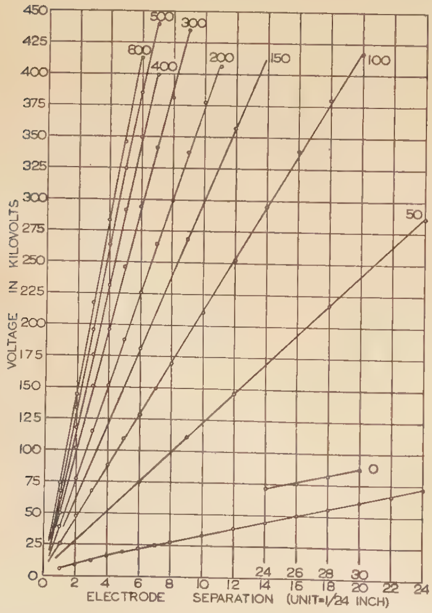


Figure 5. Breakdown voltages for plane electrodes in air at various constant gauge pressures

Figure 7 shows the effect of electrode conditioning on the breakdown voltage for a one-fourth-inch separation. The upper curve applies to well-conditioned electrodes, and the two lower curves to roughened electrodes; roughening has reduced the breakdown voltage by a factor of only two in this case. The two remaining curves apply to electrodes which have been partially conditioned. Both show the significant fact that conditioning is completed at the lower pressures before it is at the high ones. The curve which exhibits a maximum is of interest in that it shows how a carefully taken set of measurements may yield entirely misleading results. A considerable amount of conditioning was effected during the taking of these measurements because a number of spacings were studied at each pressure; only the results for the one-fourth-inch separation are given. The different points on this peaked curve therefore correspond to different amounts of electrode conditioning. This is not true for the other curves because their points were taken in quick succession using only one separation. The peak occurred because an amount of conditioning sufficient to compensate for the 100-pound reduction in pressure accrued between the time the one-fourth-inch point was taken at 600 pounds and the time the corresponding point was taken at 500 pounds. The anomalous results obtained by Ceruti,[4] where he found breakdown voltages increasing faster than either pressure or separation, may well have been caused by conditioning phenomena.

The conditioning process is evidently an electrode phenomenon. To verify this the sample of gas was changed (pressure = 500 pounds) when conditioning was partially complete and again when fully complete; in neither case was the breakdown voltage affected. Furthermore it seems that it is the irregularities on the electrodes which are responsible for the reduction in breakdown voltage; the sparking presumably burns off the irregularities. A compelling reason for believing this is that at small spacings tiny flashes can generally be seen on the surface of rough electrodes at the instant of sparking. They disappear by the time the conditioning process is completed. That the irregularities involved are extremely small is evidenced by the fact that no surface was produced which did not need some conditioning; the most satisfactory one was made by using the finest sandpaper, then crocus cloth, and finally buffing with rouge on a cloth wheel.

Other investigators have also mentioned that the breakdown voltage is augmented by operation of the apparatus; Wien[49] gives numerical values indicating a 20-per-cent improvement with use. Evidently a variety of results can be obtained for a given set of conditions with any apparatus and it is, therefore, necessary when reporting results to specify definitely the conditions under which they were taken. It is not unreasonable to suppose that part of the lack of agreement among the results of the different workers may arise from this source, since the magnitude of the conditioning effect may be large.

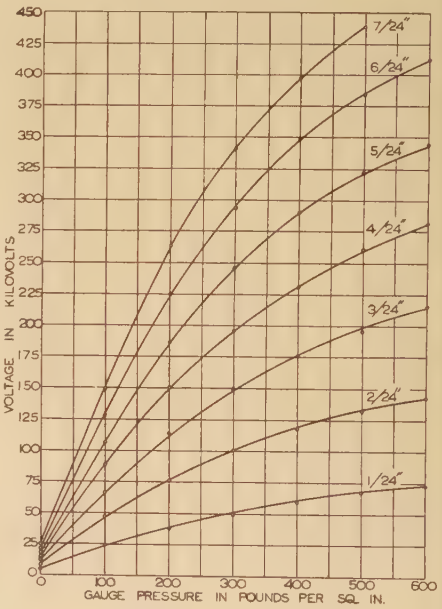


Figure 6. Breakdown voltages for plane electrodes in air at various constant spacings

The present procedure of quoting fully conditioned values may be misleading. It was done because these were the only values which were found to be reproducible. From an engineering standpoint it would seem that they are much too optimistic. From the standpoint of making comparisons with other results it leaves something to be desired because the amount of conditioning possible with each apparatus is presumably different.

But how can tiny irregularities on the surface of the large electrodes produce such a reduction in the breakdown voltage? In order to understand this it is necessary to know the important physical aspects of the breakdown mechanism at higher pressures. A knowledge of these processes is also necessary to explain the results obtained with fully conditioned electrodes and the reason for the failure of Paschen's law here.

It was mentioned earlier that in the ordinary sparking phenomenon for the common gases the important mechanisms are probably the so-called $\alpha$, $\gamma$, and $\eta$ processes, with the additional consideration of field distortion due to space charge. Photoionization was also mentioned for long sparks in mixed gases. These processes are doubtless also at work at the higher pressures.

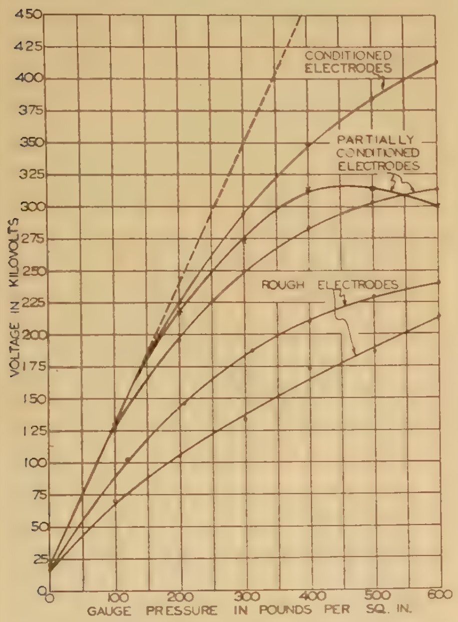


**Figure 7. Effect of electrode conditioning on the breakdown voltage for plane electrodes in air at one-fourth-inch spacing**

It has been suggested that the role of space charge becomes increasingly important as the pressure is raised and that the field distortion produced by it is the reason for the failure of Paschen's law at higher pressures. The assumption is that at pressures below ten atmospheres the effect of space charge is small and the field is uniform. The density of the space charge increases with the pressure and at about ten atmospheres it is sufficient to cause the gradient at the cathode to rise above the average gradient; at this time the breakdown voltage ceases to rise linearly with the pressure. Indeed, the hypothesis seems plausible, but it does not explain the detrimental effect of electrode roughening. Surely it teaches that the breakdown is initiated in the overstressed cathode region and that only the cathode irregularities are of importance. Roughening only one electrode should, therefore, introduce a polarity effect. This experiment was carried out and it was found that sanding the surface of one electrode reduced the breakdown voltage for both polarities by approximately the same amount.

The space-charge hypothesis may be modified to explain the lowering from roughnesses by assuming that self-sustaining point discharges are set up on the minute surface irregularities. Since a discharge of this type may exist on either a positive or a negative point, the detrimental effects are not restricted to roughnesses on the cathode. Lowering from points on the cathode could be caused by the space charge as explained above. Lowering from points on the anode might be due to the chaining of electron avalanches as discussed with the results for the point-to-plane configuration.

The existence of point discharges seems more reasonable when the current flow is considered. Figure 8 shows the current-voltage characteristic for plane electrodes at various stages of the conditioning process (one-fourth-inch separation, 500-pounds pressure). The actual numerical values should not be depended upon because they vary a great deal. It will be observed that this characteristic always has the shape one would expect for a point discharge. Further, it is difficult to account for current of this magnitude without assuming that a self-sustaining discharge exists; it definitely cannot be accounted for on the basis that it is the normal predischarge current which was discussed in connection with figure 2.

The point-discharge assumption is also consistent with the fact that roughnesses are less effective in producing voltage reductions at low pressure. Here the mean free path is longer than at high pressure, and only a few irregularities are of sufficient magnitude to permit the discharge to be established. The first few sparks remove these and conditioning is complete. At higher pressures, where the mean free path is reduced, point discharges can take place from smaller irregularities. Those are probably more numerous, making it necessary to pass many sparks before the conditioning is complete.

That the current-voltage characteristic retains its shape and the current its approximate magnitude throughout the conditioning process is also in harmony with the hypothesis. For very rough electrodes the discharges easily take place from the big irregularities and only a relatively low voltage is required. When the larger irregularities are removed a higher voltage is required for the discharge, and the curve for the current is shifted along the voltage scale as was shown.

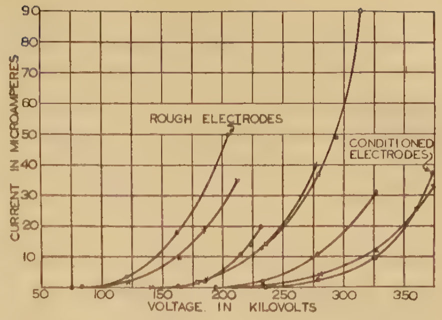


**Figure 8. Effect of electrode conditioning on the current flow between plane electrodes (air at 500 pounds, one-fourth-inch spacing)**

The point-discharge hypothesis is further fortified by a second method of conditioning the electrodes. It was found that conditioning could be effected by maintaining the voltage just below the breakdown value for relatively long periods of time. Conditioning amounting to perhaps 80 per cent of that realizable by sparking could be produced in 20 or 30 hours. The self-sustaining point discharge tends to remove the irregularity on which it was formed, and in these long periods this could produce a goodly amount of conditioning. It also seems probable that this method would not be capable of carrying the conditioning as far as the sparking process would carry it.

The space-charge hypothesis and the modification of it that has been suggested are not the only plausible processes which apply to breakdown at high pressures. It has also been suggested that Paschen's law fails because the gradient at the cathode becomes so high that field emission initiates breakdown. At ten atmospheres, where the law begins to fail, the average gradient is somewhat less than $0.4 \times 10^6$ volts per centimeter. The actual gradient is modified by the presence of space charge as well as by surface irregularities, and it may be possible under existing conditions that field emission becomes an important process. This hypothesis is easily able to account for the reduced breakdown voltages found with the roughened electrodes. But it certainly demands that roughnesses on the cathode are the important ones, and therefore that a polarity effect should exist. The absence of such an effect appears to be an irreconcilable contradiction of the hypothesis.

Another possibility is that the effect of the high field enters by lowering the potential barrier at the cathode, thus facilitating the escape of electrons.

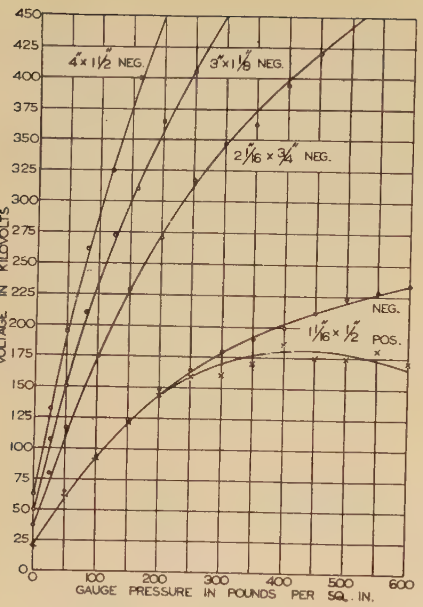


**Figure 9. Breakdown voltages for cylindrical electrodes in air (inside cylinder positive and negative)**

Either the $\gamma$ mechanism, which assumes that positive ion bombardment of the cathode regenerates primary electrons, or the $\eta$ mechanism, which assumes that photoelectric effects at the cathode regenerate the initial electrons, could be aided by such a field. Certainly this would occur at gradients lower than the values which are necessary for cold emission and the resultant lowering would set in gradually. This hypothesis, like that for field emission alone, is admirably suited to explain lowering of the breakdown voltage by irregularities on the cathode, but fails to account for the absence of a polarity effect.

Of the hypotheses which have been presented, only one seems to be consistent with the observations relating to the voltage lowering with rough electrodes and the current flowing between them. But this does not mean that the point-discharge hypothesis is to be used alone. Indeed it is able to explain only the voltage lowering due to irregularities and does not account for the failure of Paschen's law that is observed at higher pressures with fully conditioned electrodes, unless it is assumed that the electrodes can never be entirely free from irregularities which are important at the higher pressures. There is some evidence to support even this assumption in that it was found that there was always some current flow at high pressures prior to sparking.

Another phenomenon that was observed at low as well as high pressures is that after a delay of ten hours or more it was generally found that the first few sparks occurred at a somewhat reduced voltage. This is understandable if one supposes that minute irregularities are produced on the surface either by rusting action or by the settling of dust particles on the surface.

## CONCENTRIC CYLINDERS

The results for the four sets of cylindrical electrodes are shown in figure 9. The smallest pair of cylinders showed a clear-cut polarity effect at the high pressures. The larger ones showed a decided polarity effect, and in addition the measurements for them were especially uncertain for the positive polarity (inside cylinder positive). For this case there seemed to be no definite breakdown voltage which could be reproduced. At the higher pressures the values ranged from about 50 to 80 or more per cent of the breakdown voltage for the negative polarity. In this respect the behavior of the cylinders was somewhat like that of the positive point-to-plane configuration. This might be expected since the cylinders present a less severe case of a nonuniform field. A conditioning effect was also present; however, the improvement with sparking was often suddenly terminated by a burst of sparks and a great reduction in the breakdown voltage. The voltage usually improved with further operation, but the lowering was ultimately repeated. This behavior suggests that the sparking did not always improve the electrodes, but sometimes damaged them. For the negative polarity the cylinders behaved like plane electrodes with regard to conditioning.

It is something of a surprise to find that the positive polarity supports the smaller voltage at high pressures. The field emission hypothesis, the modification of it, and the space charge assumption, all indicate that the reverse ought to be true. The point discharge proposition is again the only one of those proposed which seems to agree with the experimental results.

In the present case of a nonuniform field the self-sustaining discharge must always be formed on the inner cylinder. Then to account for the polarity effect observed, it is necessary to assume that at high pressures the positive point is somewhat more effective in producing voltage lowering than the negative point. One might also conclude that its action is somewhat more erratic since measurements for the positive case were always characterized by some uncertainty. This is in agreement with the results obtained for needle points, which will be discussed in the following section.

Throughout the experiments tiny flashes could be observed on the inner cylinder at the instant of sparking. As with the plane electrodes, currents were associated with roughened surfaces and the current was reduced by conditioning.

Table I shows that only two experimenters have previously studied breakdown as a function of pressure for concentric cylinders and that both have used alternating potentials. The polarity effect reported here is evidently new. The results of Finkelmann,[11] which show that the alternating voltage increase above ten atmospheres is small for air and $N_2$, agree with those reported here for direct potentials.

## NEEDLE POINT TO PLANE

For the needle-point-to-plane arrangement only a few typical results can be included. Measurements were made on a number of gas samples for the electrode spacings, one-fourth inch, one-half inch, one inch, and two inches. Quantitative results will be given only for air and for one spacing.

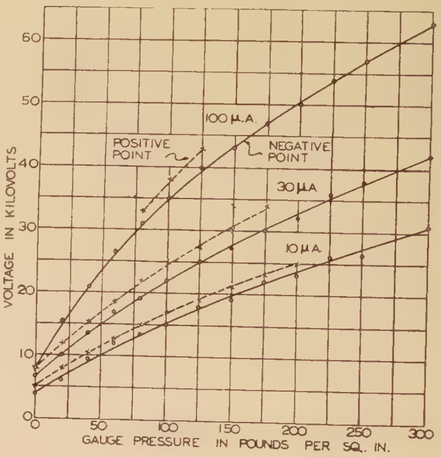


**Figure 10. Voltages to produce specified currents in air with point-to-plane electrodes spaced one-fourth inch**

The results for the needle-point-to-plane arrangement can best be introduced by considering figure 10. Here the voltages required to spray definite currents of 10, 30, and 100 microamperes are plotted as a function of pressure for both polarities of the point. It will be observed that the voltage does not increase as rapidly as the pressure and that it is not greatly different for the two polarities. Also, the curves for positive polarity do not extend above 200 pounds per square inch. The reason is that above this pressure a steady point discharge cannot be maintained from a positive point; a spark occurs instead. The curves for the negative point are arbitrarily stopped at 300 pounds;

they extend to 600 pounds, and no doubt beyond.

That a critical pressure exists is shown in another way in figure 11. Here the upper curves represent the sparking voltage for a positive point and the lower curves show the normal current flow just before sparking occurs. The voltage rises until a pressure of about 100 pounds is reached, then it becomes uncertain and may have any value between the two curves shown, finally at 150 pounds dropping suddenly to the initial potential curve. The initial potential is the voltage at which the point discharge and, therefore, appreciable current flow start. The current curve behaves in a somewhat similar manner. Two important exceptions are that it falls to zero above the critical pressure and that it exhibits a peak at low pressures. It will also be observed that the critical pressure is not 200 pounds as it was for the set of curves shown in figure 10. The reason is that the former results apply to a new needle point, whereas these apply to one that had been dulled by use. The dull point was employed because it does not change appreciably with a reasonable amount of sparking. It is a significant fact that the critical pressure is lower for a dull point than for a new one.

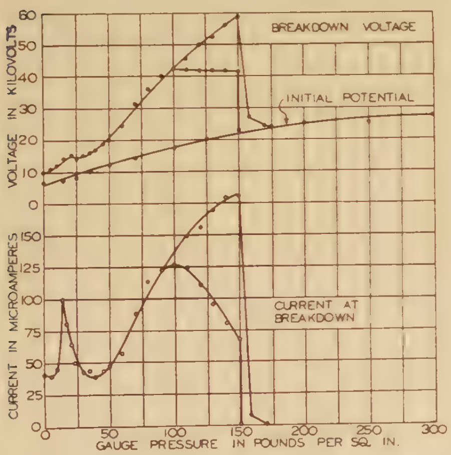


**Figure 11. Voltage and current characteristics for positive-point-to-plane electrodes spaced one-fourth inch in air**

The sudden rise in the current curve at very low pressures is associated with a change in the appearance of the visible discharge. At atmospheric pressure a dull point maintains a glow just at the tip of the needle, though sometimes a faint beam extends across to the cathode. When the pressure is increased a few pounds, the discharge (usually a glow but sometimes a brush) suddenly lengthens and the current rises. At first it extends across to the cathode, but it shortens and the current drops rapidly as the pressure is further raised. With still higher pressures the current again increases but the dimensions of the discharge continue to diminish. The shortened discharge takes on a variety of forms and each gives a different result; hence measurements are difficult to reproduce.

Visual observation of the sparks from a positive point revealed that they behave in a peculiar way. At low pressures they pass straight across the gap. This continues to the 100-pound point, which marks the start of the uncertain measurements. At this pressure the sparks do not always follow the shortest path but are spread out. The spreading becomes more pronounced as the pressure rises until the critical pressure is reached, then it becomes very slight again. Thus, spreading of the sparks seems always to be associated with uncertain measurements.

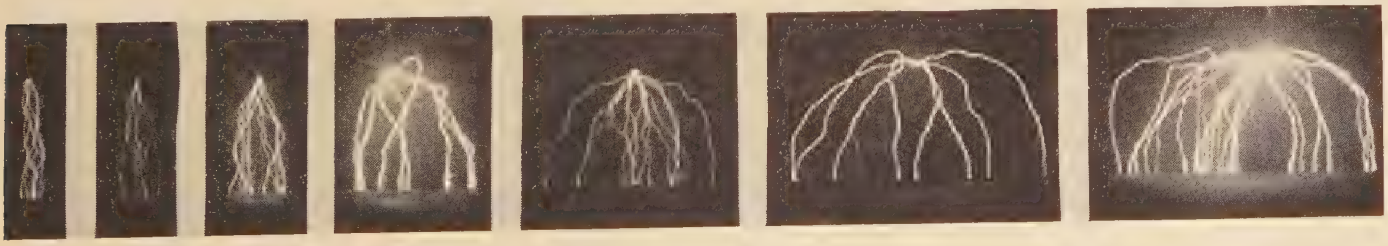
The photographs in figure 12 illustrate the type of results that can be obtained; the spreading was observed for all spacings. Each exposure shows a number of single sparks spaced about one-fourth or one-half minute. It will be observed that the sparks leave the point at many different angles and some travel a short distance in the direction away from the plane electrode. Some of the photographs suggest that the sparks never follow the shortest path when the spreading is manifest. The possibility could be investigated by making simultaneous observations from different angles, but this was impossible with the apparatus used.

The results for a dull negative point are shown in figure 13. The voltage curves are typical of all that were obtained for negative points. The current curves for other conditions, however, sometimes exhibited a minimum value. Sparks from a negative point always followed the shortest path and the steady discharge always existed as a glow of approximately constant size.

The current-voltage characteristic for both positive and negative points was studied as a function of pressure. It was found that for either polarity the shape was substantially independent of pressure. Figure 14 shows the results for a one-half-inch separation; six sets of data are plotted for the positive point (0, 15, 30, 50, 100, and 150 pounds pressure), and five sets of data are given for the negative point (0, 100, 200, 300, and 400 pounds). When reduced to a percentage basis the curves for different pressures are in surprising agreement. In making the computations the breakdown voltage was taken to be the 100 per cent voltage and the normal current flow corresponding to a voltage just below the breakdown value was taken to be the 100 per cent current.

The results that have been given for the positive point can be understood by considering the space charge left by the electron avalanche as it moves toward the point. At low pressures the density of the space charge in the avalanche path is too low to cause significant field distortion. Furthermore the ions are quickly moved out of the avalanche path by diffusion. As the pressure increases, the density of space charge in the avalanche path rises and diffusion decreases with the result that at higher pressures the field does become distorted by space charge and the ions remain in the path of the avalanche for relatively long periods of time. Under these conditions the space charge filaments constitute new points toward which other electron avalanches may be directed. The pressure at which the spark spreading starts is that for which the space-charge filament is dense enough to direct electron avalanches to itself. The fact that the space charge concentration remains for a relatively long time permits the effective electrode configuration to be built up in peculiar forms through a series of successive avalanches, and thus when the spark occurs it is led to the point over long and irregular paths. The measurements are uncertain because the electrode configura-

**Figure 12. Spark spreading for positive-point-to-plane electrodes spaced one inch in air**



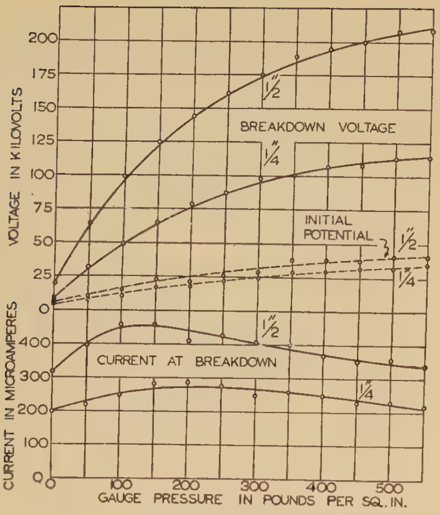


**Figure 13. Voltage and current characteristics for negative-point-to-plane electrodes spaced one-fourth inch and one-half inch in air**

tion is uncertain. That the pressure at which the uncertain phenomenon begins is lower for the larger electrode separation is understandable. The large number of ions in the interspace reduces the actual field in the vicinity of the point with the result that ion filaments of reduced density are able to direct electron avalanches toward themselves.

The above hypothesis readily accounts for the observed behavior of the sparks in the unstable region, but it does not explain how the chance mechanism is suddenly terminated by the appearance of a stable behavior. A possible explanation of this critical pressure is the occurrence of thermal ionization of the gas. At high pressures the large amount of heat energy developed by the avalanche is not effectively removed through diffusion and thermal conductivity. The temperature in the avalanche path rises with pressure until it becomes sufficient to dissociate and ionize the gas molecules and when this happens a new type of sparking mechanism presumably sets in. The point discharge causes, through progressive thermal ionization, the effective point to be projected toward the cathode until breakdown results. On this sort of basis it is reasonable that the sparking potential should coincide with the initial potential, and that scattering of the measurements and uncertainty of the spark path should cease.

Another possible interpretation of the positive point behavior is that the space charge near the point reduces the gradient at the apex, as previously suggested, until the actual gradient there is less than the gradient in the radial direction from the side of the needle. When this happens the sparks leave the needle radially in order to follow the strongest field. Since they would all tend to avoid taking the shortest path, this would explain the photographs that show no short paths. In this connection it would be helpful to establish whether or not any of the sparks follow the shortest path.

The existence of a critical pressure may also be explained on a space charge basis. Normally the geometric field of a point-to-plane arrangement is such that the point discharge is stable. But as the pressure is raised the amount of space charge in the interspace is increased and this makes the actual field more nearly uniform. Finally the tendency of the space charge to make the field uniform overcomes the stabilizing nature of the geometrical arrangement to such a degree that a stable discharge cannot be maintained.

It has been mentioned that a negative point does not exhibit the uncertain region or the critical pressure which has been discussed. This can be understood since the electron avalanche inherently spreads as it moves away from a negative point and therefore does not permit filaments with a high space-charge density to be realized. Also the field at the apex of the needle is increased by the space charge and not diminished.

In order to test the thermal ionization hypothesis the studies so far described for air were repeated for nitrogen, again for helium with three per cent nitrogen, and finally for a mixture containing equal partial pressures of the two gases. The ions involved in the breakdown are nitrogen ions in all these cases. Since the helium has more than six times the thermal conductivity of nitrogen, the helium-nitrogen mixtures carry the heat energy out of the avalanche paths more rapidly than nitrogen. The nitrogen ions also diffuse more readily through helium than through nitrogen. Because of these two effects, thermal ionization in helium-nitrogen mixtures should not begin at as low a pressure as in nitrogen alone.

The experiments showed definitely that the critical pressure is much higher for the helium mixtures than for nitrogen. The results for a one-fourth-inch spacing showed that the critical pressure was 190 pounds for pure nitrogen, approximately 500 pounds for helium mixed with three per cent nitrogen, and 350 pounds when equal partial pressures of the two gases were used. Similar results were obtained for other spacings. Either thermal conductivity or diffusion or both would cause the results for equal partial pressures of the two gases to fall midway between the others as they do.

The spreading of the sparks was smaller for nitrogen and for helium mixed with three per cent nitrogen than it was for air. But for equal partial pressures of the two gases the sparks spread as much or more than they did for air.

An experiment by Goldman and Wul[13] for pure nitrogen at 100 degrees centigrade showed that the critical pressure at this temperature was greater than it was at 13 degrees centigrade. About half of the rise they observed was due to the change in the density of the nitrogen with temperature. An increase was still manifest and this was probably largely caused by the increased diffusion at the higher temperatures. Their results were also in harmony with the thermal-ionization hypothesis.

One bit of interesting information that came out of this study of points is that the dissociated oxygen which resulted from the discharge caused a very rapid rusting of the electrodes and the tank walls. A brown dusty appearance could be detected after very few hours' operation. The deposit was collected for some time and analyzed spectrographically. It was found to be principally iron, nickel, and chromium, with traces of impurities likely to be found in the metal.

The results of this section indicate that additional difficulties would be encountered if electrostatic generators of the belt type were to be operated in compressed gases at pressures above the critical pressure. It appears that the operating requirement which specifies that the two parts of the belt be equally and oppositely charged cannot be met when positive charge cannot be sprayed on the belt. The results also reveal theoretical information which is of interest in the study of breakdown at high pressures. This is of importance since evidence is at hand

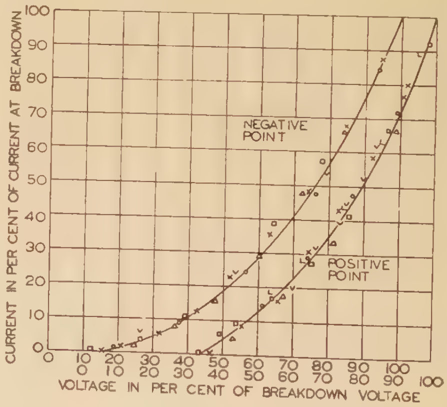


**Figure 14. Current-voltage characteristics for point-to-plane electrodes in air at various pressures**

to indicate that the point discharge is of particular significance in all high-pressure breakdown, especially when rough electrodes are employed.

## Conclusions

Breakdown measurements made with plane electrodes were found to be greatly reduced by surface roughnesses, the percentage of reduction increasing with pressure. Both visual observations and current measurements lend strong support to the belief that the lowering is brought about by point discharges proceeding from the irregularities. Prolonged sparking was found to reduce the detrimental effect of roughening. Experiments demonstrated that this beneficial effect is definitely not brought about by changes produced in the air sample. Both the effect of electrode roughnesses and the conditioning phenomenon are of real practical importance. The significance of electrode roughnesses at high pressures may make measurements under laboratory conditions appear too promising.

The cylindrical electrode arrangement showed a definite and surprising polarity effect; the measurements were lower and more uncertain when the inside cylinder was positive. Further, it was not possible to realize complete conditioning for the larger cylinders. Applications of compressed gas using a cylindrical arrangement should naturally employ a negative polarity on the inner cylinder when possible. This may be accomplished in the case of a d-c cable, but not of course in the common condenser application where alternating potentials are used.

With the needle-point-to-plane electrode configuration the two polarities yielded entirely different results. The voltage and current for a positive point increased with pressure for the first few atmospheres, then became indeterminate, and ultimately a critical pressure was reached at which the voltage fell to the initial potential value and the current to zero. In the pressure region where the measurements were indefinite the path that the spark followed was uncertain. Above the critical pressure the spark path again became regular and the voltage was definite. The results for a negative point showed no irregularity.

The critical pressure for nitrogen and for air was substantially the same, approximately 200 pounds; for helium mixed with three per cent nitrogen it increased to about 500 pounds; for equal partial pressures of the two gases it amounted to 350 pounds.

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## Discussion

**G. C. Nonken** (General Electric Company, Pittsfield, Mass.): Alvin H. Howell is to be commended on his review of the past work done on the dielectrics of high-pressure gases. Likewise, on his own work which has extended the combined voltage-pressure range to a considerably higher value than has previously been recorded.

It is of practical importance to compare the breakdown strength of air at high pressures with the breakdown strength of other typical high-voltage insulation. The important thing that shows up in such a comparison is that whereas the d-c breakdown of compressed air expressed in volts per mil is constant for different spacings as shown by Mr. Howell's figure 5, the dielectric strength in volts per mil of solid and liquid dielectrics drops off very rapidly with increased spacing. (The breakdown strength of solid insulation varies about as the two-thirds power of the spacing.) In making three typical comparisons we find that the d-c breakdown strength of five-mil thickness of good solid insulation is over three times higher than the same thickness of compressed air at 500 pounds pressure; the d-c breakdown strength of one-half-inch good solid insulation is slightly stronger than a half-inch of air at 500 pounds pressure; while 0.1 inch of transil oil is only about one-third the strength of air at 500 pounds pressure with d-c applied voltage. These comparisons would undoubtedly be much different on the basis of alternating or impulse voltages instead of direct voltage, or if the comparisons were made with other than parallel plate electrodes. It appears that if high-pressure gas is to be used as a dielectric, it will be in the ultrahigh-voltage field, where the insulation spacing is an inch or more.

In 1935, I made some tests on the corona current on a point-to-plane gap in air. I observed that the corona current, when the point was negative, was composed of a series of high-frequency current pulses which involved frequencies higher than 1,000 kilocycles. These current pulses built up very rapidly and then fell off exponentially to zero. The frequency of occurrence of these pulses was quite regular and increased with the applied voltage. With a positive point, a pulsating corona current occurred at the first initiation of corona, but at slightly higher voltage, the corona current changed to a steady state. These pulsating corona currents point to the important part which space charge has on the mechanism of breakdown. I would like to ask Mr. Howell if he observed this pulsating-corona-current phenomena in his tests, and if so, would the microammeter which he used record correctly the average value of these high-frequency currents.

I have observed the critical pressure in the breakdown versus pressure curve of sharp-edged gaps; similar to that shown in Mr. Howell's figure 11.

One test setup consisted of rod gaps tested with 60-cycle voltage in nitrogen. The critical pressure for that arrangement was 140 pounds per square inch gauge, and was not typified by such an abrupt discontinuity in the voltage breakdown curve as is shown in figure 11.

**G. W. Dunlap** (General Electric Company, Schenectady, N. Y.): Mr. Howell has done a very creditable piece of work and his paper presents valuable additions to the growing fund of information about the dielectric strength of gases at pressures above atmospheric.

Several questions arise and perhaps some related findings from the experience of the writer in a similar investigation may be pertinent.

The comments about the mechanism of breakdown are quite interesting and throw a new light on this phase of the subject. A better understanding of this mechanism is, of course, vital to the application of gases under pressure to the insulation problem. Regarding this point, the following questions might be answered.

Does not the same mechanism account for the departure from the Paschen relation with "uniform fields" as well as the critical pressure effect found with the point plane? It would seem to be a matter of degree.

Inasmuch as all the tests reported were made with direct current, it is possible that the full importance of space charge is not appreciated. This effect is more apparent when voltages with different time-amplitude characteristics are applied. For example, a six-centimeter rod gap in nitrogen at four atmospheres absolute was found to have a breakdown value of about 150 kv with 60-cycle voltage and a value of only 120 kv for a $1^{1}/_{2}$ x 40 positive impulse. This is, of course, directly opposite to the usual relation between impulse and 60-cycle breakdown.

In the study of dielectric breakdown it is well to be careful in drawing conclusions about the mechanism of breakdown on the basis of currents flowing before breakdown. Insulation studies in general have shown a decided lack of correlation between such current conditions and the actual breakdown.

Also can atoms remain in a metastable or excited state long enough to effect the strength of a given volume of gas for a time in the order of tens of seconds? In tests where positive impulse voltages were applied to sphere and rod gaps in gases under pressure it was found that the strength of a given gap depended to some extent on the preceding voltage application. Almost invariably the application of an impulse at some level within the range of voltages that could produce breakdown would cause a flashover if there had been a flashover on the previous application. Conversely, if there had been no flashover on the preceding application, the same voltage would be withstood and the voltage could be raised to the upper limit before a breakdown would occur. Impulses were applied at intervals of approximately one-half minute so this phenomenon is not satisfactorily explained by the usual conceptions of ionization by impact or electric or thermal stress.

Concerning the effect of roughening the electrodes, was any relation noted between the amount of effect and the spacing of the electrodes? It seems reasonable that the presence of small points could produce changes of the magnitude reported. Experience of the writer in corona studies seemed to indicate a measurable effect from irregularities of microscopic size on bare copper cables for high-voltage transmission lines.

Figure 11 of the paper shows a maximum breakdown voltage at 150 pounds though the conclusions give a value of 200 pounds. Was any relation noted between the critical pressure and electrode spacing? For standard one-half-inch square rod gaps in nitrogen the writer found breakdown voltage maxima at four atmospheres absolute for both positive impulse and 60-cycle voltages. There was some indication that this critical pressure decreased with increasing gap lengths.

The attack on metal parts mentioned as due to dissociated oxygen should be remembered if application is to be made where frequent breakdowns could occur. Similar trouble has been experienced where gases of complex molecular structure have been used. The use of an inert gas such as nitrogen obviates this difficulty.

In the engineering application of gases under pressure it is important to remember the wide range of dielectric strengths obtained by varying such factors as the field configuration and the polarity of applied voltage. This is emphasized by the results given by Mr. Howell. It is impossible to design gas-insulated apparatus on the basis of a pressure-breakdown curve for one gap.

**Victor Siegfried** (Worcester Polytechnic Institute, Worcester, Mass.): Mr. Howell has presented a fine piece of work on a very important line of research, and is to be commended on the thoroughness with which the investigation was made. Many of the features of high-pressure gaseous insulation have been determined and the limits within which developments may be expected for an application of gas under pressure for insulation are shown to be elastic but high as compared with practice up to the present. Mr. Howell's discussion of the effects noted with regard to conditioning of electrodes is particularly appropriate. It is obvious that for any commercial development of long lengths of cable, little or no conditioning effect will be realized and that the real practical limit is established by results for rough electrodes, as shown in figure 7 of his paper.

An investigation of pressure relations with gas for a dielectric at Worcester Polytechnic Institute has shown similar results to Mr. Howell's, in that for unconditioned electrodes, there is a distinct disagreement between points on the breakdown curve taken with increasing pressure and those taken with pressure decreasing. The trends are quite definite, and it seems to make little difference as to the order in which the tests are made. The specimen used is a concentric cylinder with a ratio of outer to inner diameter of about four, flashed over with alternating potentials, and of a length so that previous sparking of the gap produces little conditioning, since as soon as one spot becomes conditioned, another point takes the arc under approximately the same conditions as the first. This gives rise to the belief that the effect is more than an electrode effect entirely, yet it is difficult to understand how the gas can be affected directly by the direction of pressure change. The factor of time seems to play no part, as the gas can be left at any pressure for a length of time on either curve and still show a wide separation between rising and falling pressure values. The investigation of this phenomenon would help in arriving at the practical limits for gas-pressure insulation.

I would like to suggest another point of significance from the practical side of the discussion. The ratio of cylinder diameters at very near to $\epsilon$, as used by Mr. Howell, gives results which will seldom be achieved except under laboratory conditions. The interesting values of this ratio are those slightly above $\epsilon$, since the corona-free breakdown given by the curves in this paper is a very special type of spark-over. Further work of the same caliber as Mr. Howell's should be undertaken with a wide range of cylinder diameter ratios. Results from such a set of tests may help to clear up some of the baffling phenomena observed and possibly improve the test procedure to a point where observations will not be affected by sudden bursts of violent sparking, since some corona will be present to initiate slow discharge before complete breakdown ensues.

Mr. Howell has attempted to explain many of his results from fundamental concepts, but has had to throw out many possible explanations because they do not fit one observation, namely, the lack of difference in breakdown voltage for a reversal of polarity. I do not see how the polarity can be definitely biased for plane electrodes, and for cylinders the results are already counter to polarity theory; so that my own feeling is that there may be more to Mr. Howell's explanations than he has allowed on the basis of the one key observation. I hesitate to suggest that his work is in error, for I can certainly do no better than he has done, but it may be that the sensitivity of the measurements does not permit easy detection of a polarity effect which may be present.

**R. C. Buehl** (Massachusetts Institute of Technology, Cambridge): The excellent paper of Mr. Howell naturally raises the question of the extension of the results to higher pressures and alternating voltages. In this connection, two questions are of importance, namely:

1. Does the breakdown approach a definite maximum with increase of pressure, or continue to rise at a slower rate than at low pressures?
2. Will electrodes condition themselves or deteriorate when breakdown measurements are made with alternating voltages from a transformer so that each breakdown is followed by a short-time arc?

The answer to these questions for plane electrodes is contained in measurements on nitrogen with 60-cycle alternating current made by the author in 1935 with the apparatus sketched in figure 1 of this discussion but not previously published. The nitrogen was partly purified by passing over magnesium heated to 400 degrees centigrade and through a trap cooled by solid $CO_2$. Errors due to time lag were eliminated by irradiating the gaps with ultraviolet radiation from an iron arc but this had no appreciable effect on the breakdown voltages except to make them more consistent. A resistance of 1.8 megohms was used as a series resistance to protect the electrodes from excessive pitting. After a breakdown, the voltage was removed in a fraction of a second by a relay.

The breakdown voltages are plotted against pressure in figure 2. Below 15 atmospheres there was little spread in the breakdown measurements, all the values falling within two per cent of the average, so that the electrodes seem to have been satisfactorily conditioned. This conditioning required about 50 breakdowns. Above this pressure, the spread on the breakdown voltages became much greater, becoming as great as 15 per cent in some cases, the spread being shown by the shaded areas in figure 2. In general, each successive breakdown voltage would tend to be higher than the previous one until a maximum was reached but occasionally an arc would appear to damage the surface so that the following breakdown measurements would be at the bottom of the spread. Consequently, with the apparatus employed, the condition of the electrodes appeared to be continually changing in the range from 15 to 45 atmospheres. An interesting phenomenon was observed, namely, that sparks which lasted only a fraction of a half cycle often occurred at the lower breakdown voltages. These conditioned the electrodes so that the following breakdown voltage was always considerably higher.

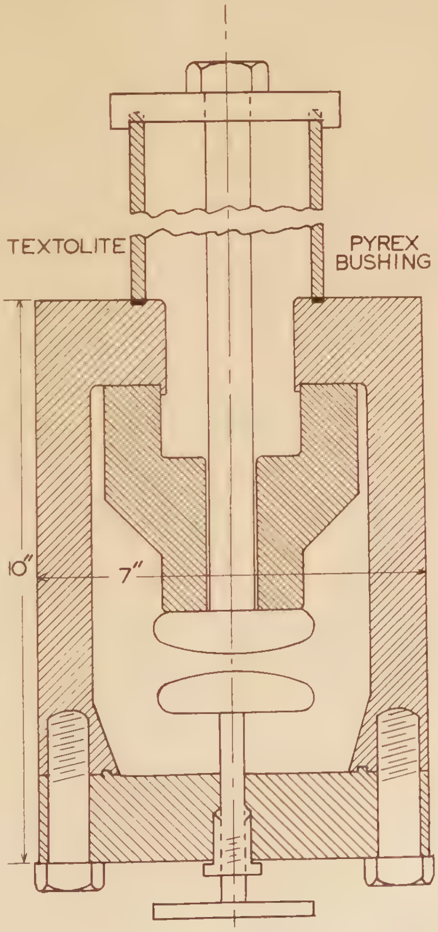

Figure 1. Apparatus employed for breakdown measurements on gas at high pressures

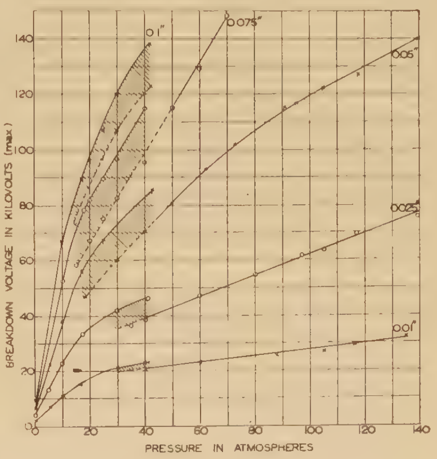

Figure 2. Breakdown voltages for nitrogen with plane electrodes at various constant separations

Above 45 atmospheres the spread in the breakdown voltages again became small except that the sparks of short duration mentioned above occurred occasionally at voltages below those necessary to cause a repeated breakdown during each half cycle. These low breakdown voltages are not shown in figure 2. Since the extrapolations of the curves from high pressures coincide with the minimum breakdown values observed between 15 and 45 atmospheres, it appears that the irregularities on the electrodes—either points or active regions of low work function—become more important at high pressures, and their effects cannot be removed as readily by breakdown above 45 atmospheres as below. Above 45 atmospheres the breakdown voltage increases about linearly with the pressure but the rate of increase of breakdown voltage with pressure is only about one-fifth that at atmospheric pressure. This corresponds roughly to the ratio of the slope of the curves for rough electrodes at high pressures to the slope for conditioned electrodes at atmospheric pressure given by Mr. Howell in his figure 7. From this it would seem that surface irregularities, which act as points of local discharge or sources of electrons, play an important role in determining the breakdown voltages at high pressures. Although the mechanism of breakdown at high pressures is probably different from that at atmospheric pressure, the surface irregularities probably control the breakdown voltage and largely mask the effect on the breakdown voltage of a change in the mechanism of breakdown.

**E. W. Davis** (Simplex Wire and Cable Company, Cambridge, Mass.): The author has carried out a most careful investigation of this subject and has gathered together a very good background of past experimental work.

The art of cable manufacture is moving forward quite rapidly and a very large number of new types of cables use or contemplate using pressure-type insulation to obtain increased dielectric strength and greater reliability. This present paper dealing as it does with gas should be of some value for gas-filled cable and of considerable use for future cable design for high-voltage d-c transmission.

The experiments with cylinders are of particular interest to us and it is hoped that future work with cylinders of varying ratio of $D$ to $d$ will be tried and also that tests with alternating potential will be made. The choice of a fixed ratio of $D/d = \epsilon$ was perhaps a wise one for this initial work. Breakdown tests of cables having varying ratios of $D/d$ do not follow the theoretical formula for large ratios of $D/d$ (over value of $\epsilon$) and as yet no good explanation has been offered.

Minimum stress, maximum stress, current density (pyroelectric effects), and corona-type formula have been offered without much success. In connection with this problem we are interested in the erratic behavior of concentric cylinders having the inside one positive and also with the pronounced polarity effect found which is apparently new. If this polarity effect is pronounced it is conceived that for alternating voltage there may be some rectifying action taking place which would allow the building up of space charges and explain the reason why corona-type formula apply fairly well to cables insulated with solid-type dielectrics.

The author is to be congratulated on avoiding many of the pitfalls in dielectric strength tests which sometimes lead to erroneous conclusions.

**A. H. Howell:** The gentlemen who have offered discussions have presented valuable material and the writer wishes to express appreciation for these contributions.

Mr. Buehl's results with alternating voltages appear to be in agreement with those for direct potentials reported in the present paper. It is especially helpful to have available these quantitative results from his work.

The comments of Mr. Davis are especially significant because of his close association with the commercial aspects of insulation problems.

Mr. Nonken has made interesting comparisons of the dielectric strengths of typical solids and liquids with those presented for compressed gases. Regarding the question he raises concerning the possible pulsating nature of the currents that were observed, this was not checked and there were no observations indicating that the current possessed this pulsating quality. The microammeter used would be expected to read correctly the average value of high-frequency pulsating currents.

The suggestion of Mr. Dunlap that the mechanism underlying the critical pressure effect for a positive point-to-plane electrode arrangement may account for the departure from the Paschen relation with uniform fields at higher pressures seems reasonable. This is not necessarily true since numerous physical processes are at work in the breakdown of a gas, and as yet there is insufficient evidence to determine whether the one responsible for the critical pressure phenomenon is wholly responsible, partially responsible, or not at all responsible for the failure of the Paschen relationship.

It has been suggested that metastable atoms may not play a part in the breakdown when the time lag is of the order of tens of seconds. Whether or not metastable atoms are important in the breakdown of a gas is determined not by the time lag, but rather by whether they live long enough to travel from the point where they were created to the point where they regenerate electrons (the cathode) which contribute to the discharge.

A definite answer to the question concerning the magnitude of the effect of electrode roughening for different electrode separations was not obtained in the present study. The question was raised but not explored. The few results obtained did not show much of an effect with separation.

The effect of electrode spacing on the critical pressure has been raised. The critical pressure for a given positive point was practically independent of spacing for the spacings used (up to two inches). It was observed that the particular point used affected the critical pressure, the pressure being lower for a dull point than for a sharp one. However, the pressure at which spark spreading and uncertain measurements began was lower for the larger spacings.

The remarks of Mr. Dunlap concerning the effect of the gaseous products of breakdown on the apparatus and of the importance of such factors as field configuration and polarity in design are most significant.

Mr. Siegfried raises the question of a polarity effect with plane electrodes. The polarity effect was expected only for the arrangement of one conditioned electrode and one rough electrode. On the assumption that breakdown is initiated at the cathode (and is not influenced by the condition of the anode) as it is with some of the suggested mechanisms, such a gap ought to exhibit breakdown voltages corresponding to rough electrodes when the rough electrode is the cathode and breakdown voltages corresponding to conditioned electrodes when the conditioned electrode is the cathode. This difference in voltage would easily be detected and was the effect expected.

The results of Mr. Siegfried's own work are very interesting and it is helpful to have the comments from his practical point of view.

# Bus Protection

## AIEE-EEI COMMITTEE REPORT*

THE RECENT occurrence of several serious switch-house fires has occasioned an unusual interest in the matter of bus protection. Acting upon the belief that a comprehensive survey of modern practices in such protection would be of some benefit to those interested, the relay subcommittee of the AIEE protective devices committee and the relay subject committee of the Edison Electric Institute electrical equipment committee jointly prepared and circulated a rather extensive questionnaire on the subject.

It is the purpose of this report to present factual data on the principal types of bus protective schemes as reported by the 34 companies replying to the questionnaire, and also to present a discussion of the design features involved as indicated by the replies to specific questions asked and collateral data supplied.

### Classification of Bus Protective Schemes

In order to obtain as much uniformity as possible in the scope of the replies solicited, the three principal types of bus protection were defined as follows in the questionnaire:

*A. Differential Protection.* The bus protective relay is operated from a differential connection of current transformers located in all sources to and feeds from the bus and therefore distinguishes between bus and external faults by virtue of its connection.

This system offers protection against phase faults, ground faults, or both, dependent upon the use of phase relays, the use of a neutral relay only, or of the latter in combination with phase relays.

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* A report prepared under the auspices of the relay subcommittee of the AIEE protective devices committee and the relay subject committee of the Edison Electric Institute electrical equipment committee by J. H. Neher, chairman of the AIEE relay subcommittee and engineer in charge of relay design for the Philadelphia Electric Company, Philadelphia, Pa., and H. L. Wallau, chairman of the EEI electrical equipment committee and electrical engineer of the Cleveland Electric Illuminating Company, Cleveland, Ohio.

*B. Fault Bus Protection.* The normally grounded parts in the station are interconnected through a "fault bus" which is connected to the station ground through one or more current transformers in such a manner that currents due to ground faults occurring on the bus or associated equipment must pass through this fault bus and operate a bus protective relay connected to the above mentioned current transformers. As indicated, this system offers protection only against faults involving ground.

*C. Partial Differential Protection.* The bus protective relay is connected to current transformers located in one or more of the sources to the bus. Operation on external faults is prevented by:

1. Utilizing an overcurrent relay with a time setting selective with the rest of the system protection under the prevailing conditions.
2. Utilizing a distance relay with a definite ohmic pickup set above the value of reactors located in the sources to or feeds from the bus; or a distance relay with a time-distance characteristic set selectively with the rest of the system protection.

This system offers protection against phase faults, ground faults, or both, according to type, and connections of the relays employed.

## Numerical Data

The numerical data obtained from two general questions covering the main constructural and operational features of the installations are given in table I. Because of wide variations in the number of installations reported by individual companies, there have been incorporated both the number of reporting companies and of installations of each class reported. In general, no effort has been made to minimize the discrepancies appearing in the tabulation because of incomplete detail in the replies.

Of the total installations, three companies reported 61 per cent and six companies reported 81 per cent of the type *A* installations; three companies reported 62 per cent of the type *B* installations, while the type *C* installations were much more uniformly distributed among the reporting companies.

On the basis that all similar applications were installed at the earliest date listed by the reporting company and applied to the total bus sections so reported, it appears that type *A* installations have been in use for 11 years, type *B* for 10 years, and type *C* for 7 years to the beginning of 1938. It will be noted that this has a tendency to exaggerate their actual age.

Group phase bus construction is used in 93 per cent of the sections equipped with type *A* and in 87 per cent of those equipped with type *C* protection. The type *B* fault bus systems are primarily favored for use with indoor installations, some 82 per cent being so reported. The margin of the isolated phase installations over the group phase for type *B* is not as great as might be expected.

The voltage ranges were selected to emphasize the grouping points of the numbers of reported installations.

In respect to the type of faults protected against, the answers were tabulated as specified on the individual returns, except that type *B* installations were listed under "ground faults" only. In some cases they were specified in the "both" category and undoubtedly these installations will function properly for phase-to-phase faults involving ground. This is probably true of all the installations listed under "ground faults." Both *A* and *C* types of protection may have installations listed in the "both" category with the same thought in mind.

As regards the matter of system grounding, practically all cases involving an isolated neutral apply to distribution substations. The majority of the fault bus installations are used in connection with limited ground currents since most are installed in generating stations where this is a standard practice.

The balance current relays employed are principally of the percentage-differential type. Distance relays are of the impedance type.

One company lists 172 type *A* installations with instantaneous overcurrent relays. Sixty-six percentage-differential relays listed under "balance current" in type *A* installations are in use by another company.

It is apparent that the type of current transformer used depends primarily on the type of bus construction. The bushing type is heavily favored with the differential class of protection since most of the protected buses are of the outdoor type. In the case of the fault bus type of protection, most installations are indoors, which makes the wound type of transformer convenient.

The "combination" group contains examples of all possible groupings of the three principal classifications.

Four companies reporting about 300 installations practically all of the differential type, use the term "excellent" to indicate performance in lieu of numerical data.

## Causes of Incorrect Operations

This information is sufficiently important to justify the inclusion of more

**Table I. Summary of the Constructional and Operational Features of the Bus Protective Installations Reported**

| Classification | Total Installations | | Type of Station | | | Type of Bus Construction | | | | Voltage of Protected Bus (Range in Kilovolts) | | | | Protection Against | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Group Phase | | Isolated Phase | | | | | | | | |
| | Existing | Proposed | Generating | Transmission | Distribution | Indoor | Outdoor | Indoor | Outdoor | 2–9 | 11–22 | 33–88 | 110–220 | Phase Faults | Ground Faults | Both |
| *A.* Differential | 26/803 | 9/38 | 20/172 | 21/379 | 14/288 | 16/245 | 24/533 | 5/49 | 1/10 | 6/100 | 22/338 | 14/252 | 14/153 | 9/266 | 8/47 | 22/484 |
| *B.* Fault bus | 11/197 | 2/5 | 9/132 | 7/42 | 4/28 | 5/75 | 5/15 | 7/90 | 1/22 | 1/6 | 9/165 | 4/24 | 2/5 | | 12/198 | |
| *C.* Partial differential | 9/132 | 4/37 | 7/62 | 6/53 | 3/54 | 7/77 | 8/70 | 3/21 | 1/1 | 2/32 | 8/104 | 1/4 | 4/29 | 4/53 | 2/24 | 8/90 |
| Totals | 32/1132 | 15/80 | 28/366 | 27/474 | 15/370 | 22/397 | 27/618 | 14/160 | 2/33 | 7/138 | 28/607 | 16/280 | 17/187 | 10/319 | 18/269 | 25/574 |

| Classification | Type of Grounding System | | | | Type of Relay Protection | | | | | Type of Current Transformer | | | | Number of Operations | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Overcurrent | | | | | | | | | | |
| | Solid | Resistor | Reactor | Isolated Neutral | Induction | Instantaneous | Both | Balanced Current | Distance | Bushing | Through | Wound | Combination | Total | Incorrect |
| *A.* Differential | 20/415 | 15/333 | | 5/87 | 11/258 | 8/386 | 3/41 | 16/150 | 1/4 | 21/613 | 10/121 | 10/52 | 6/30 | 13/155 | 10/32 |
| *B.* Fault bus | 6/62 | 5/121 | 1/8 | | 4/14 | 7/91 | 3/94 | | | 2/39 | 2/51 | 7/97 | 1/3 | 10/55 | 5/15 |
| *C.* Partial differential | 7/92 | 6/39 | 2/4 | 2/10 | 4/53 | 2/25 | 1/4 | 3/47 | 2/19 | 5/69 | 4/37 | 4/37 | | 3/4 | 1/1 |
| Totals | 22/569 | 16/493 | 3/12 | 6/97 | 16/325 | 14/502 | 7/139 | 16/197 | 3/23 | 21/721 | 13/209 | 19/186 | 7/33 | 22/214 | 16/48 |

NOTE: The figures to the left of the oblique bars designate the number of reporting companies while those to the right of the oblique bars designate the number of bus sections reported.

detail from the individual returns.

| Number of Incorrect Operations | Causes |
|---|---|
| 8 | Incorrect wiring. |
| 4 | Errors in routine testing, such as applying potential to the ground bus. |
| 1 | Differential relay failure. |
| 5 | Improper application, principally failure to consider current transformer ratio changes under high fault currents. |
| 3 | Construction errors. In one case this was a matter of poor contact and in another construction men inadvertently cut into an operating bus protective setup and the third was caused by vibration from construction on an adjacent panel. |
| 2 | Failure of bushing current transformers. |
| 2 | Balance circuit grounded. |
| 1 | Auxiliary relay failure. |
| 8 | Faulty insulation of fault busses. Other cases of this are mentioned. |
| 8 | Minor miscellaneous causes. |
| "Several" | Unbalance created by d-c transients at the time of a fault. |

## Maintenance

Maintenance of bus protective systems is quite evenly divided between the "negligible" and "reasonable" categories. No reporting companies consider the maintenance of their present bus protective systems as "heavy."

The usual maintenance periods reported by the various companies are as follows:

3 months—reported by 3 companies with 71 installations

6 months—reported by 11 companies with 480 installations

12 months—reported by 15 companies with 434 installations

24 months—reported by 2 companies with 157 installations

Included in the above tabulations are some companies with a relatively large number of installations which divide them into two categories in order of importance and provide maintenance accordingly.

A 6- and 12-month interval is so used by three companies with 227 installations. Two companies with 277 installations use 12- and 24-month maintenance periods.

Four companies reporting 287 installations provide some or all of these installations with instruments on which the condition of the balance is read three times daily.

Several companies provide tripping tests and/or inspections at intervals between the normal maintenance periods given above.

## Design Features

A number of specific questions were asked in reference to the three main protective systems, intended to promote a discussion of certain features fundamental in their designs, and the following discussion has been prepared from the replies. Outlines are also included of special bus protective schemes which are believed to be of general interest.

### DIFFERENTIAL BUS PROTECTION

(*a*) *Current Transformer Considerations.* The highest ratio of fault current to current-transformer rating varies considerably and attains the remarkably high value of 126 to 1. The conservative limit of 10 to 1 or less is used by five companies reporting 316 installations. The most commonly used limits are within the range of 11 to 20 to 1. Twelve companies report 300 installations in this group. The 21 to 30 to 1 class has a substantial representation consisting of 138 installations reported by seven companies.

Higher limits are used by three companies reporting 66 installations which are probably permissible because of special conditions. A conservative trend is clearly indicated by a consideration of proposed installations. These show that the limiting ratios will be lowered by five companies and raised by one and will exceed 20 to 1 in one case only.

Eight companies reporting 264 installations include an accuracy limitation in current-transformer specifications. Classification of these is difficult since most of the specifications are not complete and lack agreement. The limits range from 0.5 per cent to ten per cent at ten times rating.

Nineteen companies reporting 546 installations use standard transformers with commercial accuracies. However, a growing consciousness of the accuracy factor is apparent as three of the latter companies now include some specification of accuracy in proposed installations.

Opinion favors the independent grounding of current transformers. Eighteen companies reporting 307 installations follow this practice. Seven companies reporting 394 installations use a common ground, generally located at the relay panel and providing a convenient point to megger the relaying circuits.

One company reporting 179 installations uses a single ground for all installations except those on 4.8-kv busses which use independently grounded current transformers. Of particular interest is the fact that these ground connections, in recent practice, are made up of a 300-ohm resistor with a parallel gap. This reduces the hazard of a false operation if the circuit is accidentally grounded and at the same time is believed to afford adequate safety to personnel and equipment.

With a single exception no inclination to change existing practice is indicated in the proposed installations.

A relatively even division of opinion exists on the permissibility of utilizing current transformers of different ratios equated by autotransformers with 14 companies reporting 288 installations subscribing to this practice and 12 companies reporting 523 installations avoiding it. Of the latter, two companies use balancing transformers if a transformer bank is included in the protection. Balancing transformers are all of the autotransformer type with the exception of those used by three companies who prefer the tapped two-winding type.

It is evident that balancing transformers should preferably be avoided whenever possible, but sufficient evidence exists to indicate that it is perfectly feasible to use them if the situation requires.

If protection against ground faults only is provided existing current transformers are generally used according to reports from nine companies with 175 installations. Separate current transformers are used by three companies reporting 11 installations. Both types are used by one company reporting 9 installations.

The preference is decidedly for the common neutral return where existing current transformers are used. This is the practice of six companies reporting 155 installations as compared to three companies reporting 20 installations, which make use of insulating current transformers in the individual neutral circuits. No nonmagnetic conduit is used in any installation.

Proposed installations of this type favor the use of existing current transformers and are quite evenly divided between insulating current transformers and the use of the common neutral return.

A very general freedom from open-circuit current-transformer troubles is indicated by the fact that 19 companies reporting 464 installations find it unnecessary to make any provision to check for this condition, except by reading the various currents at the time of the periodic relay check.

Three companies reporting 124 installations make use of fault detectors in series with the differential relay. This permits of an alarm indication in case the differential relay alone should operate due to an open current transformer.

Three companies reporting 197 installations use one-ampere ammeters in the neutral circuits which are read three times daily. A similar check is made by one company using the harmonic-restraint type of relay by means of a low-reading high-resistance a-c voltmeter connected across the internal current transformer of the relay.

Twenty companies reporting 640 installations test for a short-circuited condition in the current transformers at the time of the relay check, usually annually. The procedure is divided between the companies which read load current values in the various branches of the differential circuit and the companies which apply an external voltage to determine the impedance of the circuit.

One company reporting 110 installations applies to the relay daily a potential which is too low to cause it to trip. The value of the resulting current will determine an open- or short-circuited condition. Another company reporting 11 installations makes a monthly tripping test with a small transformer just adequate to trip the relay under normal conditions.

Five companies reporting 51 installations make no check for short circuits following initial installation.

(*b*) *Differential Relays.* Phase differential relays are usually set above maximum load current of any circuit, according to 13 companies reporting 531 installations, and settings range as high as three times this value. Seven companies reporting 63 installations set phase relays below maximum load values.

In the case of neutral relays, the situation is reversed with 2 companies reporting 17 installations with settings above the maximum load and 11 companies reporting 413 installations using settings below this value.

Considering both neutral and phase relays which are set below maximum load values, 12 companies reporting 343 installations find it unnecessary to make any provision to prevent tripping due to accidental opening of a current transformer. On the other hand, six companies reporting 98 installations use fault detectors in series with differential relays to prevent the occurrence of faulty trippings on this account, and one company uses percentage differential relays for the same purpose.

Both schools of thought find results satisfactory since the majority of the proposed installations involve no change in practice.

Percentage differential relays are employed in 107 installations reported by 13 companies. Considerable diversity of opinion exists as to the most desirable grouping of current transformers.

Four companies reporting 77 installations group sources to one winding of the relay and loads to the other. This number includes the largest user of percentage differential relays for bus protection, a company with 66 installations. Similarly two companies with 7 installations use three-winding differential relays and group sources to one winding, loads to another, and bus ties to the third.

Two companies with 11 installations connect the principal source or sources to one winding and other sources and loads to the second. One company with 4 installations groups both sources and loads to each winding. Three companies with 5 installations include transformer banks in the differential protection and naturally group current transformers according to potential of the bank windings.

(*c*) *Prevention of Relay Operation on Transients.* Eleven companies reporting 483 installations make no intentional provision to prevent operation of the differential relay on through faults due to transients set up in the differential circuits by iron saturation in the current transformers. It is of interest to note that all of this group with the exception of two companies reporting 238 installations make use of induction relays which inherently introduce some time delay.

The largest user of instantaneous relays for bus protection, reporting 182 installations, keeps the ratio of fault current to current transformer rating within the conservative limits of ten to one. This should be of considerable assistance in providing for an iron-saturating transient. The remaining 16 reporting companies make provision for this factor in a number of ways.

Ten companies provide time delay in one form or another. Three companies use high relay settings while three companies provide high capacity or special transformers. Transient shunts are in use by one company and the harmonic restraint type of relay is installed for this purpose by another.

(*d*) *Effect of Abnormal Setups on Protective System.* As to means provided to maintain the effectiveness of bus protection when the "normal" circuit setup is temporarily changed, practice is evenly divided on the need for such protection. Fifteen companies report 362 installations with no provision for this eventuality. Comments from this class indicate that many remove entire groups of equipment from service for maintenance and others include current transformers from all possible connections. Other companies operate with inadequate protection if the weather is favorable.

Eight companies reporting 187 installations follow the practice of opening the trip circuit of the differential relay manually in case of an abnormal setup.

A small group of three companies reporting the substantial number of 249 installations use auxiliary switches on disconnecting switches which operate to open the trip circuit of the differential relay in case the normal switching setup is disturbed. In some cases one company switches current circuits to rebalance the protective system for the abnormal setup.

An interesting treatment of this problem is provided at one high-capacity generating station. Ten generator and step-up bank units feed into the 110-kv bus. Considerable flexibility is required for various combinations of units and outgoing lines. Each section of the double bus system is split into independent sections of variable lengths. To provide protection for these varying numbers of busses, the currents of all units and outgoing lines are combined through a differential overcurrent relay. The operation of this relay applies potential to a tripping bus. The individual switches on the incoming and outgoing feeds are then tripped by the individual phase and ground fault detectors with the potential from the tripping bus, thus making the protection independent of any possible grouping of circuits. An operation of the differential relay alone provides an alarm.

### FAULT BUS PROTECTION

Most of the existing installations were built integral with the station. Eight companies so report 75 installations. Four companies report 35 installations added later. Three companies with a large group of 70 installations specify both categories without providing a detailed breakdown of the installations.

The preponderance of fault bus installations with special insulation is noteworthy. Four companies report 98 indoor installations and two companies report 26 outdoor installations with special insulation. Two companies report 8 metal-clad installations which naturally fall in this group. Natural concrete insulation is used by three companies reporting 45 indoor installations and two companies reporting 5 outdoor installations.

The importance of adequate insulation for satisfactory fault bus operation is obvious. In one case a group of 4 installations was discontinued and another group of 12 installations reinsulated after a series of faulty operations due to inadequate insulation.

Practically all installations are tested initially with various high voltage and current values. Seven companies report 165 installations which are checked for insulation in periods varying from four months to two years. Where the insulation is high a high-voltage test is made and where it is relatively low a check of the current through the relay is made and compared with the total supplied at the test point. Two companies reporting 20 installations make no regular insulation tests.

In all cases the setting of the relays is based on the minimum anticipated fault current, together with a desirable factor of safety. In some installations using natural concrete insulation it has been found necessary to determine the percentage of fault current which appears at the relay for the various faults.

For similar reasons it has been found necessary at times to determine the maximum stray currents flowing through a relay for faults in adjacent sections in order to provide a setting in excess of this value.

Although two cases of faulty operation have been experienced due to accidental contact of low-voltage circuits, in general, this eventuality is not considered to be a serious hazard and no provision is made for preventing relay operation under this condition.

As a whole, experience with fault bus installations is considered satisfactory and further applications are in order for the reporting companies.

This approval is qualified for one group of 4 installations which were decommissioned because of inadequate natural concrete insulation. Another group of 12 installations was reinsulated after a series of faulty operations and are now scheduled to be changed over to a combined differential and fault bus scheme. It is thought that future installations would be of this order.

A number of companies experienced insulation difficulties with initial installations of the fault bus system, but felt that the condition was now satisfactory and that additional installations are in order.

### PARTIAL DIFFERENTIAL PROTECTION

Where distance relays are utilized, these are of the impedance type, employing wye-connected currents and phase-to-phase voltages for protection against phase faults or phase-to-neutral voltages for protection against ground faults.

Fault detectors are used in practically all installations. These consist of instantaneous overcurrent phase or ground relays, residual-voltage relays, and polyphase directional or directional ground relays polarized by station neutral current.

No especial difficulty is apparently experienced in providing an adequate safety factor in the settings of the impedance relays if arcs of reasonable lengths are considered.

### SPECIAL BUS PROTECTIVE SCHEMES

Two companies propose to install bus protection by a scheme based upon the "directional comparison" method of pilot protection of lines. The scheme provides a directional ground relay on every bus tie and feeder and an overcurrent relay in the neutral of the generator. The tripping is initiated by the operation of the neutral overcurrent relay and the trip circuit is routed in series through the front contacts of all directional relays on incoming circuits and the back contacts of all directional relays on outgoing circuits.

If the outgoing circuits have no source of ground current backfeed, overcurrent relays may be substituted for directional relays.

One company reports seven installations in which both incoming and outgoing circuits from the bus are provided with impedance relays. The incoming impedance relays are provided with a slight time delay and can be kept from functioning to trip all incoming circuits by the operation of the instantaneous impedance relays on the outgoing circuits.

### GENERAL CONSIDERATIONS

(*a*) *Hazards of Inadvertent Relay Operation.* Twenty-nine reporting companies believe that the advantages to be obtained from bus protection are adequate to justify the hazard of an incorrect operation. Two companies feel that no possibility of load loss should be incurred.

A large majority of existing installations are arranged to trip on the operation of any differential relay alone. This group includes 850 installations reported by 23 companies. Ten companies report 65 proposed installations in this classification.

Ten companies reporting 288 existing installations require or favor the use of some checking device such as a fault detector which must operate in addition to the differential relay before tripping can be accomplished. Twenty-three proposed installations reported by four companies will likely be in accordance with this policy.

One installation on an important 230-kv application makes use of two completely separate sets of differential protective equipment, including the current transformers. Both sets of relays must function to clear the bus. Either set operating alone will provide an alarm only.

The requirement of this safeguard appears universal with the partial differential type of installations.

A preponderance of existing and proposed installations favor the use of a single multicontact relay for tripping as opposed to the use of a separate auxiliary relay for each switch tripped. Twenty companies report 757 installations following this practice while 11 companies reporting 437 installations use a number of auxiliary trip relays. Among some of these latter companies it is evident that the consideration involved was not a matter of principle, but the fact that a preferred type of auxiliary relay did not have a sufficient number of contacts in a single unit.

(*b*) *Supervision of Trip Circuit.* About one-half of the companies reporting on about two-thirds of the installations use supervision of the tripping circuit through the differential relay and the remainder do not. It is probable that many of the latter did not consider the supervision of the trip circuit of the oil switch alone as belonging to this classification and it is certain that a considerable number of the former group did include these cases.

Several companies use complete supervision of the differential trip circuit if it is routed through a number of relays or through interlocks on disconnecting switches.

(*c*) *Equipment Tripped and Locked Out.* The common practice is to trip all switches on the bus, as 25 companies so report 895 installations. Six companies reporting 107 installations trip all feeds to the bus only. Two companies reporting 22 installations trip only the major feeds to a bus.

One company reporting 13 cases of partial differential protection for ground faults trips only the sources of ground current feed to the bus.

The last three companies referred to also report 220 installations which were included in the first group with all switches to be tripped.

Breaker closing circuits are not generally locked out by the operation of differential relays. Twenty-four companies with 796 installations report against this practice. However, out of this group, eight companies with 407 installations use hand reset auxiliary relays and since relays of this type are commonly used in oil-switch control practice, it is probable that many other similar cases were not considered within the scope of the question.

Six companies reporting 107 installations follow the practice of locking out the breaker closing circuit with a differential relay operation. Three companies allow one or two reclosures at automatic substations so equipped prior to lockout.

(*d*) *Hazards of Interconnected Current Transformers.* The necessary interconnection of current transformers usually involved in any bus protective scheme is not considered a hazard by 20 companies reporting 839 installations.

Nine companies reporting 341 installations believe such a hazard exists, but that it may be mitigated with insulating current transformers in the opinion of five companies with 139 installations and by separate current transformers according to two companies reporting 186 installations.

The danger referred to consists of an accidental contact of the balance circuit with high voltage and the possibility of false tripping incurred in the testing of the interconnected equipment. Several companies believe the hazards will exist in any case.

Twenty companies reporting 883 installations use independent current transformers for bus protection. Twelve companies report 133 installations where current transformers are used in common with other equipment. Three companies report 196 installations in both categories.

(*e*) *Backup Protection.* Backup bus protection is universally favored where full differential protection is not warranted. Twenty-eight companies reporting 1,011 installations are in favor of this practice while three companies with 52 installations do not follow it.

Opinion is evenly divided on the desirability of using backup protection in addition to full differential or fault bus protection. Sixteen companies reporting 500 installations follow this practice while 12 companies reporting 420 installations do not. Five companies report 285 installations in both categories.

## Conclusions

From the factual data and discussion presented, the following conclusions may be drawn.

1. There is conclusive evidence that operating companies have generally accepted the idea of providing some type of protection for busses in installations of major importance.

2. Adequate bus protection can be obtained by any of the three major methods described.

3. Maintenance of bus differential relay systems is in general no different from that of other protective relay systems.

4. While complete current differential protection is predominantly the favored method, a number of apparently successful protective schemes have been developed which are applicable to old installations, and which avoid the excessive expenditures which would otherwise be required for complete current differential protection.

5. The considerable number of installations of fault bus protection reported, particularly as applied to existing installations, contradicts the general belief that this method of protection is limited to special cases specifically designed for the purpose.

6. While considerable complexity has been introduced into the protective scheme in certain cases in order to prevent inadvertent tripping of the bus, there is considerable opinion to the effect that such refinements are unnecessary.

7. While opinion favors the use of separate current transformers for bus differential protection, it is apparent that current transformers in common with other equipment can be successfully used.

8. When instantaneous or high-speed differential relays are employed, special care should be taken to prevent the operation of the relays due to transients.

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# Discussion

**E. H. Bancker** (General Electric Company, Schenectady, N. Y.): While the factual data are interesting in indicating what is in use and in showing that there is a considerable amount of bus relaying in existence, it should be borne in mind that not everything being done is what should be done in the future. A tire worn to the cords may never have blown out before but if used long enough it will. To illustrate, take the practice of grounding differential-current-transformer secondaries at all current transformers versus at one point only. Safety rules may make the multiple grounds desirable but freedom from falsely tripping a bus from potential gradients around the station dictate a single ground. It may be years before a case of false tripping appears, but it is quite probable that in most instances the single ground was selected by those companies using it because multiple grounds gave trouble. Just one case of trouble will change the practice of the company having it. So it is with some of the other procedures in which there seems a diversity of practice. Hence in utilizing this report it is highly desirable to apply some intelligent sifting process to determine which of several courses is the better.

**W. K. Sonnemann** (Westinghouse Electric and Manufacturing Company, Newark, N. J.): This report presents an interesting résumé of design, application, and operating data on the three principal means for obtaining bus protection at the present.

The report indicates that a great deal of thought has been spent on the problem from the standpoint that, in most cases, each bus presents its own particular problem. This is true because of the great variety of factors present, and we believe that it will continue to be so for some time to come.

The operating records shown are somewhat disappointing in that they indicate a rather high percentage of incorrect operations. However, if we deduct those false operations attributed to incorrect wiring, errors in testing, improper application, and the like, all of which should tend to disappear from the picture as experience is gained, the record looks more favorable.

The problem of the adverse effects of d-c transients is one which has not always been thoroughly appreciated in the past, but which is now receiving increasing attention. "Several" false operations are attributed to d-c transients, and it is quite probable that the most of these were associated with the generating station busses, approximately 30 per cent of the total installations. The solutions presented in the paper are interesting and represent solutions designed to fulfill particular operating conditions and protection requirements. Where high-speed operation is desired, the solution of introducing time delay is not possible, of course. In such a case, the proper co-ordination of current transformer performance together with the relays applied must be given the most careful consideration. It is felt that much is yet to be learned where time of relay operation of from one to three cycles is desired.

**G. B. Dodds** (Duquesne Light Company, Pittsburgh, Pa.): This paper contains a wealth of information on present practices regarding bus differential installations and several interesting conclusions can be drawn from it.

With respect to the ages of the type *A* differential installations which the report lists as having been in use for 11 years, it is wondered if a mistake has not been made in the length of time and that it possibly should be 21 years instead. It is known that in the company with which the writer is associated, bus differential installations were in use as early as 1924 and it is possible that other companies had them in even earlier.

In regard to the number and causes of incorrect operations, it is felt that the number as given does not constitute a bad record considering the number of installations in service and the length of time they have been in service, even taking into consideration that it is known that the number is inaccurate and probably should be increased.

Consideration of the causes reveals that a number of them could have been prevented by more thorough checking after installation and others by better maintenance. The record of performance for the ensuing years should be better than the past because of increased attention being given to this type of installation and interchange of ideas as provided by this paper.

It is interesting to note the diversity of design features used by the different companies and also that each company seems to be well satisfied with its own methods of installation. In other words, they have been able to solve the problems that have arisen in a manner that is suitable to them.

**J. H. Neher:** While relay engineers are agreed that from a protection standpoint some form of bus protection should be applied to all busses of major importance, nevertheless the relative infrequency of faults on protected busses requires serious consideration in connection with the economic justification of any such installation.

Based upon the data obtained from the questionnaire which represents the experience of a probable minimum of 5,000 bus-section years of operation of bus protective systems, only one out of every $3^1/_2$

# Study of the Performance of the 3,600-Horsepower New Haven Electric Locomotives

By FELIX KONN
MEMBER AIEE

F. H. CRATON
MEMBER AIEE

IN June 1938, the New York, New Haven and Hartford Railroad placed in operation six new 3,600-horsepower a-c d-c passenger locomotives of the same general type as the ten 2,800-horsepower engines which were put in service in 1931, but incorporating numerous improved features to give considerably increased performance to meet the more exacting demands of modern high-speed transportation.

Motive power equipment, for the electrified main-line service of the New Haven Railroad, presents many problems, decidedly different from any other metropolitan district railroad electrification in this country, which are of interest to the design and to the application engineer. It is the purpose of this paper to point out the special requirements that had to be met, to give a brief description of the locomotive and of its equipment and to show by records of service tests how the engines are applied.

## New Haven Requirements

The new locomotives were designed primarily for operation in the New Haven's normal express passenger service, as represented by a maximum duty of 1,200 tons trailing (15 80-ton Pullman cars) between Grand Central Terminal or Pennsylvania Station, in New York City, and New Haven, Conn., with three intermediate stops.

### A-C D-C Operation

From Grand Central to Woodlawn Junction, about 12 miles, operation is over the New York Central's 660-volt d-c third-rail system. From Woodlawn to New Haven (60 miles), power is supplied from an 11,000-volt single-phase overhead contact system. Trains are operated also from Pennsylvania Station to New Haven (75 miles) over the Hell Gate Bridge route, operating on an 11,000-volt single-phase supply throughout. The requirement of third-rail operation necessarily complicated the equipment as combination a-c d-c units had to be provided.

### Axle Loading Restrictions

The Park Avenue Viaduct in New York City presents another problem in the design of New Haven locomotives. This structure has specially restrictive loading limitations which could not be exceeded.

### Speed Restrictions

Numerous speed restrictions which are necessitated by junctions, drawbridges, and curves, make the demands upon the equipment more than ordinarily severe by requiring many accelerations. An examination of the speed charts for express service between Pennsylvania Station and New Haven, included in this paper, shows the saw-tooth nature of the resulting operation.

### Grade Operation

From a grade standpoint, the Hell Gate Bridge route to the Pennsylvania Station is more severe than the run over the New York Central tracks to the Grand Central Station. On the eastbound run over this route the road climbs from 75 feet below sea level in the East River Tunnel to 150 feet above sea level over Hell Gate Bridge within a distance of 5.6 miles, equivalent to an average grade of 0.76 per cent and with a maximum grade of 1.50 per cent. Westbound over Hell Gate, there is a uniform average grade of 1.18 per cent for two miles.

### Seasonal Variations

The New Haven's passenger traffic is markedly affected by seasonal conditions. During July and August, week-end travel to the summer colonies on Long Island Sound puts heavy demands on the local service between New Haven and New York, while at the same time through traffic is boosted greatly by the vacation movements to New England.

## New Locomotives

It will be realized, from these special conditions of the New Haven system, that the new locomotives had to be suitable for:

Severe normal duty
Still higher seasonal peak duty
A-c d-c operation
Limited axle loading

To meet these conflicting requirements, it was imperative that advantage be taken of every possible increase in material utilization to realize the maximum performance possibility of the locomotive.

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Paper number 39-21, recommended by the AIEE committee on transportation, and presented at the AIEE winter convention, New York, N. Y., January 23-27, 1939. Manuscript submitted October 28, 1938; made available for preprinting December 12, 1938.

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reported installations has experienced an operation and 22 per cent of these have been incorrect.

Messrs. Sonneman and Dodds have commented on this operating record which would seem to be very disappointing. As they have pointed out, in a large number of cases the reasons given for incorrect operations are such that if proper care had been taken in making and maintaining the installations, these operations would not have occurred.

In regard to the matter of incorrect operation due to transients, it must be realized that the present intense interest in such matters is only a little over a year old, and was just starting at the time that the questionnaire was circulated. It is reasonable to assume therefore that when fuller knowledge is available in this respect, a number of changes will have to be made in existing installations of bus protection.

Mr. Dodds has questioned the figures given for ages of the various types of protective systems. We wish to point out that the word "average" was unintentionally omitted in this connection. The figures given represent average ages computed on the assumption that all installations of the same type reported by any company were in service at the earliest date reported.

Mr. Bancker's point in respect to the use of multigrounded current transformers is well taken and although no incorrect operations were reported as a result of this, nevertheless it seems that this practice should be avoided.

In conclusion we wish to express our thanks to the engineers of the 34 reporting companies who filled out the rather long questionnaire and particularly to Mr. Tesar of the Cleveland Illuminating Company who examined the returns and compiled the data on which this report has been based.

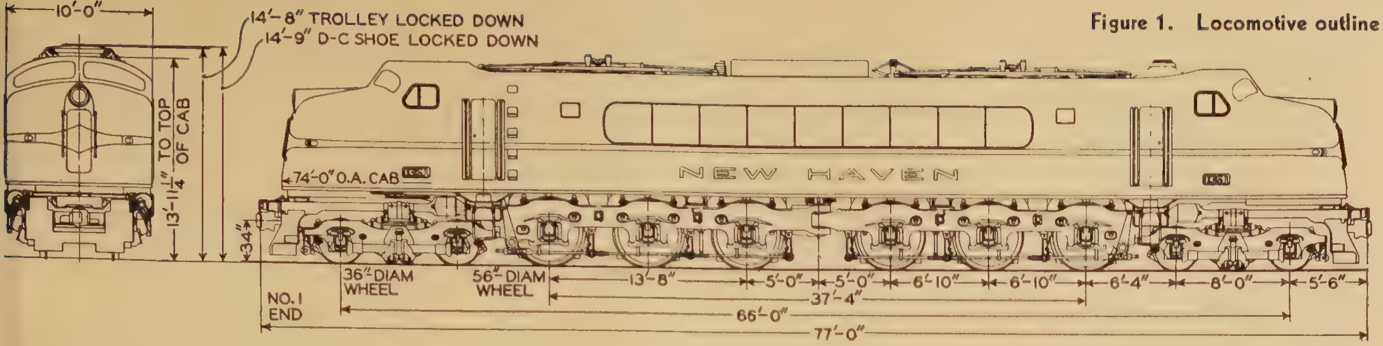


**Figure 1. Locomotive outline**

## Performance Capacity

Whereas the continuous capacity of the new locomotives is only 800 horsepower greater than that of the 0351–0360 engines, their peak output of 7,600 horsepower exceeds by 2,800 horsepower the corresponding figure for these earlier engines.

This considerable increase in peak performance capitalizes this most important asset of electric locomotives in general: their ability to draw abundant energy from the external power supply and transform it into excess performance by virtue of their overload capacity. This permits handling loads in excess of normal, on certain trains, without alteration of schedule time and, within limits, without detracting from the life of the equipment.

Because of this intermittent character of the maximum service, a locomotive designed specifically to handle the peak load continuously would be larger, and more expensive than warranted. On the other hand, to assign locomotives continuously to duty demanding more than their normally rated capacity is a questionable application, although it is being done deliberately in some cases with older equipments and with apparent success. However, to take advantage of the overload capacity of a locomotive to handle infrequent peaks, is unquestionably justified and allows realization of the maximum usefulness of a given locomotive.

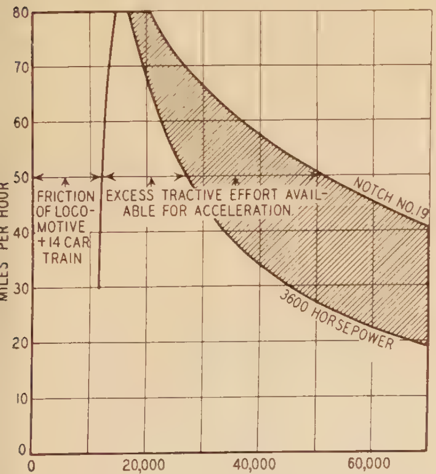


**Figure 2. Surplus power available for rapid acceleration**

The overload capacity of these electric locomotives is also normally used in everyday service to maintain high schedule speeds by quickly accelerating the train to the maximum permissible speed after slowdowns.

This is brought out in figure 2 which compares the maximum performance characteristic of these new engines with that corresponding to 3,600-horsepower axle output. The shaded area, representing extra capacity made available to the electric locomotive by the external power supply, will increase two- to threefold the rate at which the train will be brought back to top speed, thereby procuring faster service and a better utilization of the track capacity.

## Heating and Commutating Capacity

The ability of the generating, transmission, and contact system to supply the surplus power required for peak performance, must be matched by the ability of the locomotive equipment to transform it efficiently and reliably into mechanical energy. To this end, adequate heating capacity has been provided in all parts of the electrical equipment. Also, ample commutating capacity has been built into the traction motors so that they can transmit these high outputs without excessive duty on the commutators and on the brushes. In fact, the consideration of commutation influences the design and determines the size of the traction motors to a far greater extent than the heating capacity requirement, because the commutating capacity is largely determined by the fundamental constants of the motor, while the heating capacity can be increased by the use of more ventilating air. Thus, conservative commutating conditions can only be secured by conservative design constants and the six twin-armature 12-pole traction motors with which these locomotives are equipped, are especially favored in this respect.

## Control of Commutating Performance

With the basis thus laid for safe commutating conditions, special attention was given to obtaining an accurate control of the traction motor commutation throughout the entire load range.

Reduced exciting field strength is used in the new locomotives to minimize the sparking at starting, up to approximately ten miles per hour, at which speed the exciting field shunt is disconnected by the action of a phase-angle type relay.

Two commutating field settings are available in the new locomotives as in the earlier 0351–0360 units, but a new connection of a phase-angle type relay was developed to control the changeover from the low-speed to the high-speed commutation setting. The performance of this relay is truly matched to the motor. It ignores such variables as line voltage and wheel diameter and its internal characteristics insure that the change in commutating field connection is determined solely by the two factors, current and speed, which together determine the commutating condition, thereby resulting in the minimum commutator and brush maintenance.

To further insure as complete a control of commutation as possible, three indicating lights are provided, which light up in sequence as the various field contactors function and thus furnish the operating crew with a continuous check on the correct performance of the motor control equipment (figure 3).

Finally, periodic inspections and gradings established by the appearance of the commutators provide a timely warning in case some abnormal conditions might tend to increase the commutation duty.

## Ventilation

With the size of the traction motors largely determined by considerations of commutation, the amount of ventilating air was fixed by the requirement of meeting the 3,600-horsepower continuous rating of the locomotive and this, in turn, determined the pressure available for the ventilation of other parts of the equip-

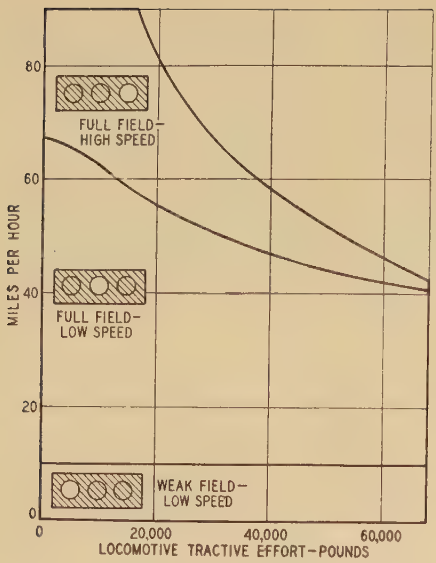


**Figure 3. Operation of indicating lights**

ment. Out of the total amount of air required on the locomotive, the traction motors use 61 per cent and the transformer, the blower motors, and the motor control units divide the remaining 39 per cent.

Because the ventilating horsepower requirement increases as the third power of the amount of ventilating air, it is very important that the amount of air to be supplied to each piece of equipment be accurately determined and adjusted.

### Commutator-Type Blower Motors

Commutator-type blower motors as used on the New Haven locomotives are especially favorable to a close adjustment of the ventilating horsepower. They can be designed for the most suitable blower speed and the availability of various voltage taps on the transformer secondary gives the possibility of a final adjustment after all the equipment is tested and assembled. Commutator type blower motors also lend themselves to considerable energy savings by being operated on a lower voltage tap at a reduced speed, consequently at considerably less power, when full ventilation is not required. Thus, when the New Haven locomotives are energized but idle, the blower speed is reduced by 30 per cent resulting in a 65 per cent saving in blower kilowatt demand.

## Service Tests and Records

Shortly after these locomotives were delivered, a series of road tests was conducted by the New Haven Railroad to verify performance in revenue service or with special test trains operating on regular passenger schedules.

Very complete records were secured by having several observers take readings every minute (or as frequently as was necessary) of speed, motor current, line voltage, controller notch, location, kilowatt-hours, etc. In addition, a continuous graphic record was taken of the motor current, which was used throughout these tests as a measure of the locomotive tractive effort available at the wheels. This is equivalent to using the series-excited traction motors as dynamometers, thus procuring with hardly any preparation an accurate record of the locomotive tractive performance.

Since the train speed variations take place gradually, it is possible to obtain a very good record of it without a recording instrument. With these two records, tractive effort and speed, synchronized by timing watches, the locomotive horsepower can be readily plotted as shown on the accompanying charts.

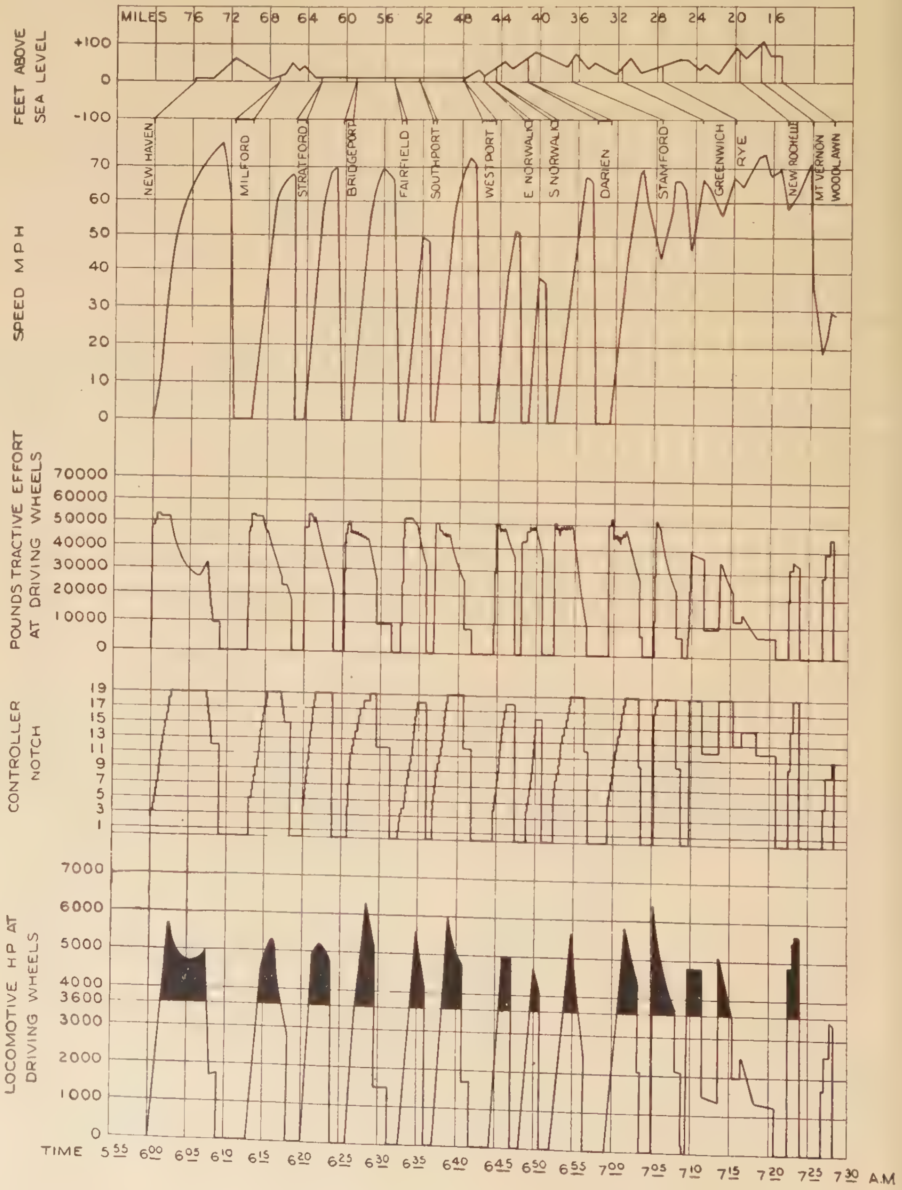
The same data have been plotted in a condensed, but perhaps more striking form, in the "minute-by-minute" records. These records can be taken directly by one observer, who reads motor current and speed every minute, on the minute, or can be plotted from the continuous records if such have been obtained. Each double reading is transcribed as a speed-tractive effort point, which takes its place in the locomotive performance range.

The interesting feature of these records is that each little dot has the same weight as any other little dot, in so far as the time element is concerned and any grouping of points indicates a zone where the engine is operated a large fraction of the time.

Records in both the continuous and the "minute-by-minute" form are shown for

**Figure 4. Continuous record, train number 367 with 15 cars, New Haven to Woodlawn**

Blackened areas show use of horsepower in excess of continuous rating



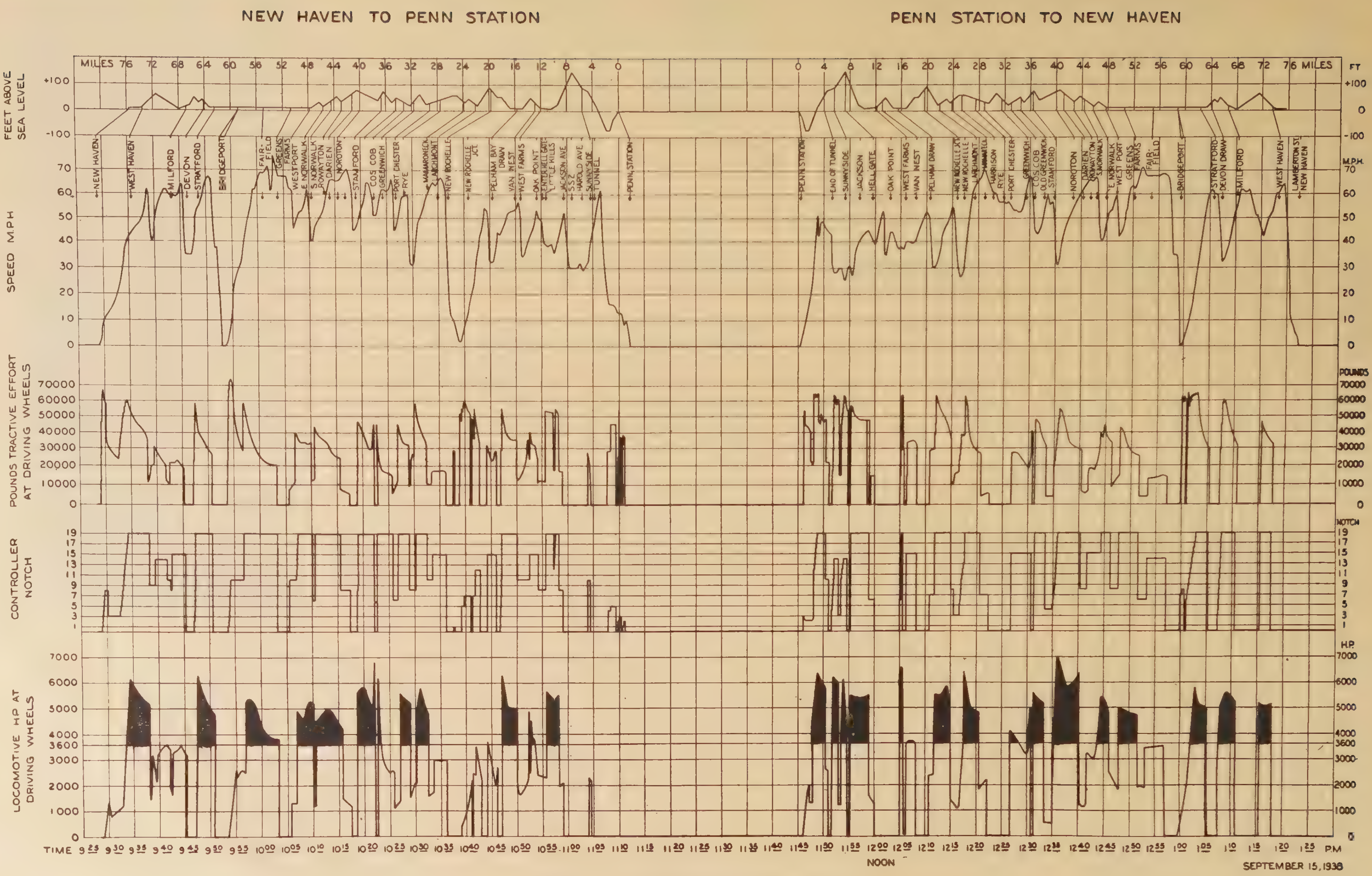


**Figure 5. Continuous record, 20-car test train**

Blackened areas show use of horsepower in excess of continuous rating

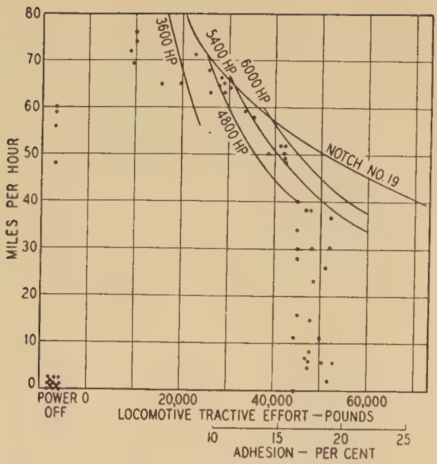


**Figure 6.** Minute-by-minute record of speed-tractive effort performance, New Haven to Stamford with nine intermediate stops; train number 367 with 15 cars

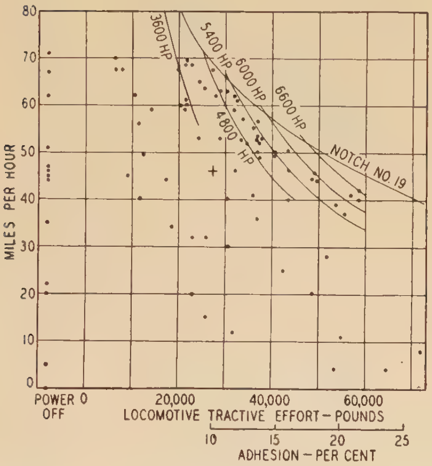


**Figure 7.** Minute-by-minute record of speed-tractive effort performance, New Haven to Pennsylvania Station* with stop at Bridgeport; 20-car test train

* Readings beyond Hell Gate not included

**Table I. 0361–0366 Locomotives for the New York, New Haven and Hartford Railroad**

| | | |
|---|---|---|
| Type | 11,000-volt a-c, 660-volt d-c high-speed passenger | |
| Nomenclature | 2 – *C* + *C* – 2 432/270, 6*GEA*622*A*, 11,000/660 volt | |
| Dimensions | See figure 1 | |
| Weights—pounds: | | |
| Total—fully loaded | 433,200 | |
| On drivers | 272,400 | |
| Per driving axle—average | 45,400 | |
| On guiding | 160,800 | |
| Per guiding axle—average | 40,200 | |
| Mechanical parts | 269,400 | |
| Electrical equipment | 163,800 | |
| Maximum safe speed—miles per hour | 93 | |
| Running gear | 2 – *C* + *C* – 2 wheel arrangement, cast steel trucks, plain journals | |
| Cab construction | Streamlined, double end, all welded, outside truss type | |
| Traction motors: | | |
| Number and type | 6*GEA*622*A* twin armature | |
| Volts—maximum per armature | 300 | |
| Method of drive | Gear, quill and spring cup | |
| Gear ratio and wheel size | 78/23 = 3.39; 56 inches | |
| Tractive effort at 25 per cent ad | 68,100 | |
| Locomotive rating—continuous: | A-C | D-C |
| Tractive effort—pounds | 24,100 | 26,900 |
| Speed—miles per hour | 56.0 | 39.6 |
| Horsepower | 3,600 | 2,840 |
| Maximum available horsepower | 7,600 | 5,500 |
| Control: | | |
| Alternating current | Electropneumatic, single unit, three circuit, single motor combination with 19 running notches | |
| Direct current | Electropneumatic, single unit, series-parallel with two running notches | |
| Main transformer | Forced-flow forced-cooled synthetic-liquid type | |
| Ventilation | Forced to all equipment by two combination blower-cleaners | |
| Blower motors | Two two-speed a-c, one-speed d-c commutator type, forced ventilated, each with overhung control generator | |
| Compressors | Two a-c d-c commutator type, self-ventilated, 100 cubic feet per minute displacement each | |
| Train heating equipment | Oil-fired steam boiler | |

two trains which emphasize the outstanding performance made possible by the overload capacity of the new locomotives (figures 4 to 7).

Train No. 367 is a high-class commuter train, operating between New Haven and Grand Central Terminal, New York. On certain days in the summer, the amount of traffic makes it desirable to handle 15 cars against a normal of 8 to 12 cars. This peak requirement demands that the locomotive be operated at the equivalent of 22 per cent continuous overload for one hour to meet the scheduled time.

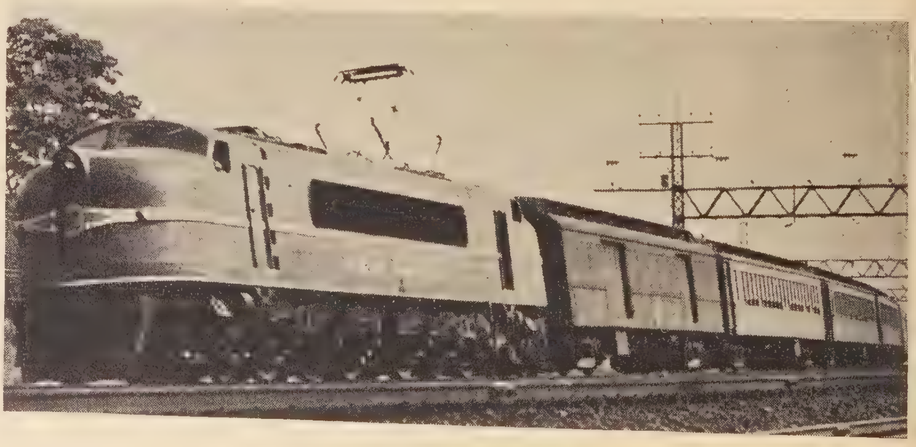
Figures 4 and 6 show the records of such a run, illustrating the use of reserve horsepower and overload capacity. Operation of this sort is approaching the performance of multiple-unit car equipment, energy consumption being 60.5 watt-hours per ton mile for the frequent-stop portion of the run. It is interesting to note how much of the time the locomotive is operating on notch 19 or the maximum available output curve.

To arrive at suitable maximum tonnage ratings, the tests already mentioned were conducted. Figures 5 and 7 show the records of a train composed of 20 Pullmans, 1,756 tons trailing, between New Haven and Pennsylvania Terminal, with one stop, Bridgeport, in either direction. The use of the high available capacity above the rating of 3,600 horsepower, as well as the large amount of time spent on notch 19 will be noted. The frequent slowdowns and the use of peak performance for rapid acceleration from the bottom to the top speed are also evident.

It can be seen from these records that the performance of this 3,600-horsepower engine is comparable with that of an internal power engine of at least 5,400-horsepower axle output, and yet the average horsepower is within the locomotive 3,600-horsepower continuous rating.

This again emphasizes the outstanding feature of these electric locomotives, the ability to make use of the overload capacity of their electrical equipment to deliver surplus performance making possible fast schedules which can be rigidly maintained because of the margin of power available to take care of any abnormal conditions. The accompanying data are offered as concrete examples of these performance possibilities of modern electric motive power.

**Figure 8.** Locomotive with train



## Discussion

**Sidney Withington** (New York, New Haven and Hartford Railroad Company, New Haven, Conn.): This interesting paper presents the importance of qualifying electric locomotive horsepower rating figures to co-ordinate them with the service to be performed by the equipment. The quantity given in the paper indicating a maximum horsepower of 7,600, while undoubtedly permissible on such service as that of the New Haven, might well be too high a figure in connection with service on some other electrified territory.

The advantages in thermal capacity of the motors are obvious in this connection, in permitting short-time overloads. It is to be noted that in the overload rating of equipment under the circumstances described, the capacity not only of the main traction motors, but of the transformers, preventive coils, etc., must be taken into account. In this connection, a comparison of the characteristics of such equipment with the characteristics of the Diesel locomotive is of interest. A Diesel engine rated at 3,600 horsepower would have no overload capacity normally, and while the 3,600 horsepower would be generally available under all conditions, it could not be exceeded even for short periods. It is, therefore, impossible to compare, without qualification, the ratings of such locomotives as those described in the paper and Diesel-electric equipment.

The modern control for single-phase motors in providing excess voltage taps, permitting thus the utilization of increased horsepower ratings at higher speeds, is one of the most notable advances in the art of locomotive design in recent years.

**E. W. Brandenstein** (General Electric Company, Erie, Pa.): You have heard Mr. Konn tell us that these a-c locomotives are so designed, from a heating and commutating standpoint, that they will absorb the huge blocks of power furnished by the transmission and distribution system.

Now what do these overload capacities give us from a practical operating and economic standpoint? Mr. Konn has explained that the total number of locomotives required for passenger service depends upon a few peak days throughout the year. On those days the train length can be increased from, say, 12 cars to as high as 20 cars, thereby taking care of a possible 60 per cent increase in passenger traffic. That is not enough to accommodate passenger peaks which come on football days, holidays, inauguration, etc. To take care of these peaks, it is necessary to add many trains and locomotives in spite of the increase in train length from 12 to say 20 cars.

Here is a real traffic overload problem. A 60 per cent increase in train weight, with the same high schedule speed, is not enough. How are we to take care of the additional trains required without increasing the total number of passenger engines? I will tell you. This overload and commutating capacity solves the problem for us. We will resort to our freight locomotive pool for the additional passenger engines required. The peak freight traffic and peak passenger traffic do not, fortunately, come on the same day. "Oh," you will say, "you can't do that. In order to do a thing like that you must have a universal engine, one that is good for slow freight and also high-speed passenger traffic." That is exactly what this overload and commutating capacity does for us. Let me illustrate it.

The Pennsylvania Railroad have a group of 70-mile-per-hour engines which are purely freight locomotives. They have another group which are 100-mile-per-hour engines that are used only in passenger service. There is still a third group of 90-mile-per-hour engines which are used in either freight or passenger service, depending upon whether the traffic peak is passenger or freight. Last October, when there was a peak in freight service, a large number of these 90-mile-per-hour engines was in freight service. During the recent holidays, a high percentage of the 90-mile-per-hour engines was in passenger traffic. The same engines which were hauling 4,500 flat ton coal trains in October were handling the high-speed passenger trains in December. You can readily appreciate that these 90-mile-per-hour universal engines are responsible for a great decrease in the total number of passenger and freight engines required.

What does this high overload and commutating ability give us?

1. Faster schedules.
2. Heavier trains at these fast schedules.
3. A universal engine.

What does this mean from an operating and economic standpoint?

1. Fewer engines.
2. Lower capital expenditure.
3. Lower fixed charges by virtue of the lower capital expenditure.
4. Lower maintenance costs by virtue of fewer locomotives.

In other words, gentlemen, I believe this overload capacity for this type of motive power is completely changing the complexion of railway electrification.

**P. H. Hatch** (New York, New Haven and Hartford Railroad Company, New Haven, Conn.): One of the inherent features of electric equipment operating from an external power supply is the ability to operate for short periods considerably in excess of continuous ratings. There is nothing new in this, and the immediate extent to which such overload operation can be carried is usually limited only by weight on driving wheels and the ability of the electrical apparatus to stand the overloading. There is, however, a long term factor which may be decidedly limiting. This is the cost of maintenance. If overloading is carried to the point where its advantages are offset or exceeded by cost of additional maintenance, then the overload characteristic of electrical equipment can be a liability rather than an asset.

In the paper under consideration, the authors describe at considerable length instances of short-time overloading of the new locomotives, but except for rather general paragraphs on heating and commutating capacity, very little is said about the effect of overloading on maintenance of the equipment.

To make the story complete, it would be interesting to know specifically what has been done to obtain high overload capacity. With a locomotive of fixed maximum axle loading, was such capacity obtained by increase in ventilation, additional iron and copper, by improvement in design, or by a combination of any of these? Was a definite overload capacity planned on, or was the determination of this left for road tests or service experience? Has any relationship been established between overloading and life of apparatus, or is this, too, left for determination in service?

Providing the high overload capacity is not seriously at the expense of maintenance, it unquestionably has very great possibilities in the design of electric locomotives. These possibilities, it is believed, warrant a full and complete discussion of the means employed to obtain such capacity.

**Felix Konn** and **F. H. Craton:** We agree with Mr. Hatch that, from the standpoint of heating as a limitation, electrical equipment has always had overload capacity at speed. We wish to point out, however, that, in the single-phase locomotives which were built up to about ten years ago, full advantage could not be taken of this feature because the output of the earlier types of traction motors (of the resistance-lead or doubly-fed type) was decidedly limited by destructive sparking at the brushes, especially at the higher speeds.

To overcome this limitation, a new type of single-phase traction motor was developed, offering not only very favorable commutating characteristics (by virtue of the low flux made possible by a large number of poles), but also the possibility of controlling the commutating performance over a wide range of speeds and currents, especially at high speeds and high horsepowers.

As pointed out by Mr. Withington, the possibility of wide range control of the traction motor voltage which is fundamental in single-phase locomotives—but which had to be held in check with the earlier types of motors—found a vigorous outlet in the modern single-phase traction motors which permit the modern single-phase locomotives, in which full advantage has been taken of their inherent fitness for "overvoltage" and "overload" operation, to deliver the higher speeds and horsepowers demanded by progressive transportation.

Mr. Brandenstein has brought to your attention some of the tremendous service advantages of these modern engines which operators have been quick to recognize and to develop. The ample horsepower reserve and the inherent flexibility of this type of locomotive offer many more possibilities in faster schedules with heavier trains and fewer locomotives and the way is open for further advances for still better and faster service to the public and the industry.

In emphasizing the importance of qualifying electric-locomotive horsepower-rating figures to co-ordinate them with the service to be performed by the equipment, Mr. Withington has brought out a glaring deficiency in our present practice of rating electric locomotives primarily on the basis of their continuous capacity.

Undoubtedly the use of the continuous rating provides a very definite "yardstick" for one of the features which determine the

# Continuous Processing for Automobile Tire Fabrics

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PROGRESS is evident to an unusual degree in the fabric-processing operations at the new automobile-tire plant of the Ford Motor Company.* The fabrics and rubbers which are run through these operations to form the rubber-fabric structures used in building the automobile tire pass through processes and machinery which clearly reflect the continuous production idea developed by the automobile industry. The electrical equipment in this plant introduces ideas which make the drives fundamentally different from those in general use.†

In these processing operations four types of rubber-fabric structures are produced: (1) ply stock, the material for the plies in the tire, (2) breaker strip stock, which goes between the plies and the tread, (3) chafer stock, used between the plies and the side walls, and (4) bead stock, from which strips surrounding the beads are made.

Fabric for the ply stock originates in a creel room from which 1,500 to 1,600 separate cords are guided from spools into parallel positions to form a broad sheet of cords without weft. Fabric for the breaker stock is the same as that for ply except that the cords are farther apart and the sheet, prepared at textile mills, is in the form of a woven fabric having a weft of very small threads. Fabrics for the chafer and bead stocks are special square-woven fabrics similar to duck in construction. From these starting points, these textile raw materials pass continuously through production lines and combinations of machines, as indicated in figure 1, to emerge as the four finished stocks.

From an electrical standpoint, the drives may be segregated into those for (1) main calendering operations, (2) bias-cutting operations in which the previously rubberized fabric is cut on the bias, and (3) slitting and coating operations in which some of the bias-cut material is slit into strips and further treated with rubber. The main calendering operations present most of the electrical problems associated with the several drives and these problems may, therefore, be

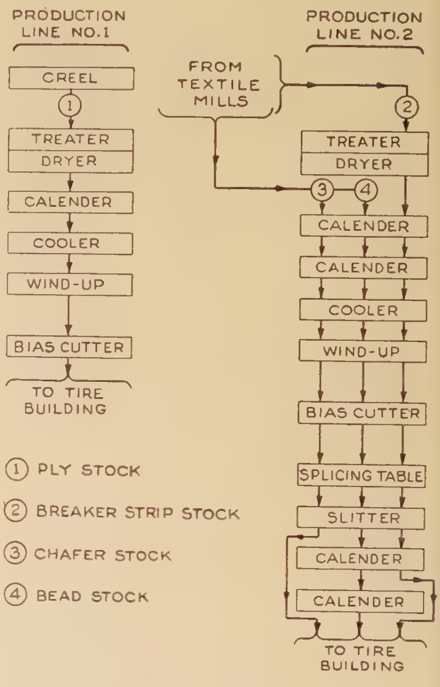

**Figure 1. Diagram of sequence of processing operations**

In production line number 1 the parallel cords from the creel are dipped in liquid rubber, passed through a dryer, and then through a four-roll calender which simultaneously adds rubber to both sides of the sheet. The calendered sheet passes through a cooler and then, with a liner to prevent sticking, is rolled up on a mandrel. The roll is transferred to a cutter where the fabric is cut on the bias and sent to the tire builders. In building up the tire the several plies are laid with the bias in alternate directions

In production line number 2 the fabrics pass through two calenders instead of one, the first calender working one side of the material and the second calender the other. The bias-cut material is spliced end-to-end on the splicing table. If the slit material passes through the final calenders a layer of rubber is laid on it at each calender

This paper discusses production line number 2 through the wind-up

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* Because of the numerous advanced manufacturing ideas which it embodies, this $5,600,000 plant located at the Ford Motor Company's Rouge Plant, Dearborn, Mich., is of exceptional engineering interest throughout. Operations are designed to keep materials moving steadily forward from the moment the bales of crude rubber are cut up and started on their way through plasticators, mixers, mills, and so on, until the finished tires emerge from final inspection. A description of the complete plant is in the *India Rubber World*, June 1, 1938.

† Acknowledgment is made of assistance from E. F. Wait, J. T. Mortley, and A. J. Walrath of the Ford Motor Company in the development of these drives.

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value of an electric locomotive. So many of the other features (such as commutating capacity or overload capacity) are open to varying interpretations that it is very comforting to find in the continuous rating of an electric locomotive a feature which can be rigidly determined and which can form a definite basis of comparison.

However, the continuous rating should be supplemented by a service rating taking into account the peak capacity, say, 7,600 horsepower, of the locomotive which is more nearly representative of the amount of work which the locomotive can do than the continuous rating, say, of 3,600 horsepower.

Mr. Hatch has asked if a definite overload capacity is planned on. We will answer that the peak capacity of the locomotive is actually the most important factor in the design of the locomotive and that this consideration far outweighs the continuous capacity in the design of the various parts of the equipment.

To safeguard the use of the peak capacity in service, improvements in design and manufacture have been backed up by a careful system of checks in the testing, assembly, and servicing of these locomotives to insure, as much as possible, that, year in and year out, these equipments will deliver their high outputs under the conditions most favorable for the life of the equipment.

As a result of this increase in service capacity and of the efforts made to secure the best service performance, the modern single-phase locomotives are covering more and more mileage every year and with low maintenance cost per mile.

Mr. Withington also brings out the difficulty of comparing a Diesel-electric locomotive and an electric locomotive, both of which have a continuous rating of 3,600 horsepower measured at the driving wheels. The Diesel electric will deliver continuously 3,600 horsepower at the wheels and will never be able to exceed this output. The electric locomotive we have discussed will deliver 3,600 horsepower at the wheels continuously and up to 7,600 horsepower for short periods of time. The difference in accelerating performance between the two types of locomotive, which is illustrated in figure 2 of our paper, will be further emphasized by the greater weight of the Diesel electric locomotive which will require a greater part of its output for its own propulsion.

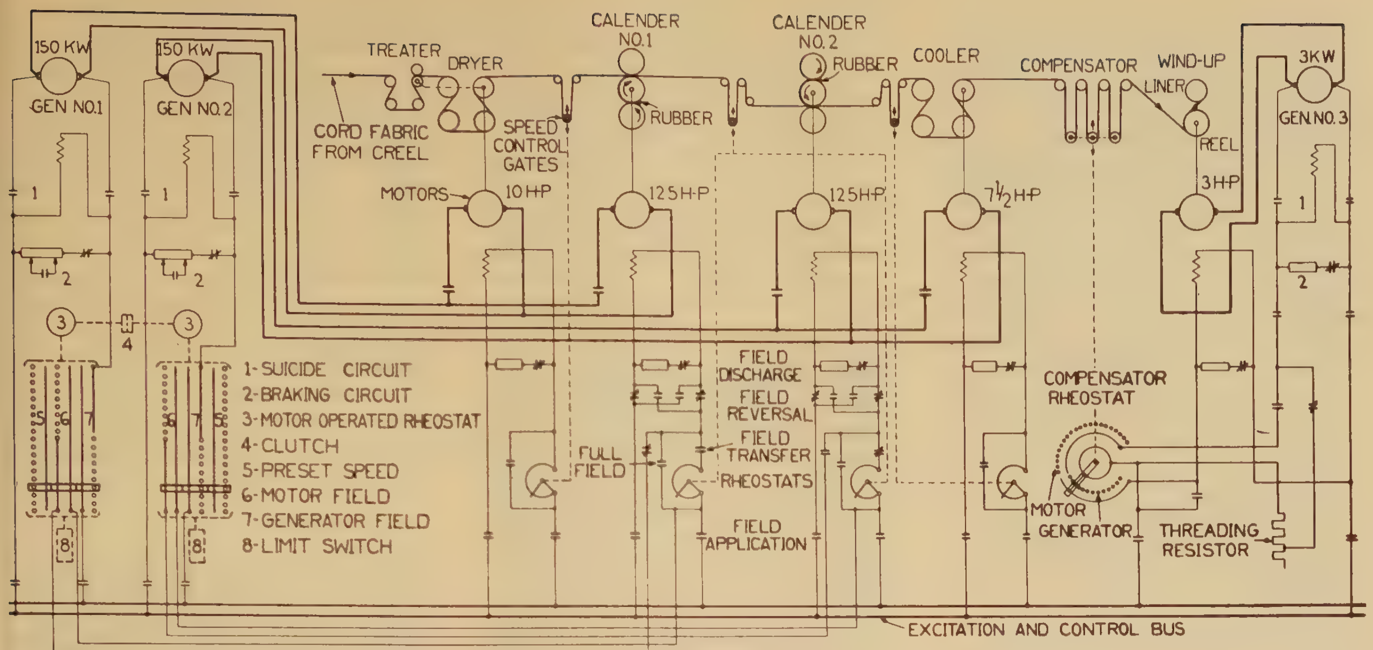

**Figure 2. Schematic diagram of the armature and field circuits for the main calendering operations**

described by considering one of the main calendering drives, schematically illustrated in figure 2.

## Requirements of Main Calendering Line

The production speed to be 5 to 35 yards per minute with the design of the drive such that the top speed can be raised ultimately to 60 yards. Operation to be continuous at any speed within the range. While starting, stopping, and operating at any rate of production, positive and automatic speed regulation to be maintained between machine sections.

Equipment to be such that production combinations are available as follows: (1) material through the entire sequence of operations, or through this sequence with any one or more of the machine sections by-passed, (2) equipment operating as two independent drives, one drive consisting of calender number 1 and the sections ahead of it and the other consisting of calender number 2 and the sections following. In this setup, also, it must be possible to by-pass individual sections.

Equipment to be such that any combination of skim-coating or frictioning can be obtained on the calenders. By way of explanation, skim-coating consists of working rubber onto the surface of the fabric while frictioning consists of working rubber down into the structure of the fabric. The calenders have three equal-diameter rolls. The motor on each calender drives the middle roll which in turn drives the two outer rolls through gearing. The fabric passes between the middle and one of the outer rolls. When the middle and outer rolls are geared so that the roll surface speeds are equal, the fabric, which passes through the calender at the roll surface speed, is skim-coated. When the outer rolls are geared to rotate slower than the middle roll, say in the ratio two to three, the fabric takes the speed of the slower outer roll and is frictioned. Therefore, for a given fabric production speed, assuming a frictioning ratio of two to three, the driving motor operates 50 per cent faster when frictioning than when skim-coating.

Lastly, calenders to be reversible; quick stopping to be available during starting and running as a safety requirement; all control operations to be magnetic and to be actuated from simple controlling stations.

## Constant or Adjustable-Voltage Drives?

Prevailing practice for calendering drives is to use adjustable-speed motors operated from a constant-voltage d-c plant system, frequently three-wire to permit doubling speed ranges by means of two armature voltages.

In the present instance, the adjustable-voltage or Ward-Leonard system of drive appeared to be particularly suited to the requirements. The smooth, relatively stepless, and rapid acceleration possible with this form of drive, the ease with which it lends itself to wide ranges in production speeds, its effectiveness where it is desired to maintain a controlled speed relation between separately driven machines, its flexibility in making the desired several combinations of the driven machines—all pointed to its adoption. In addition it offered an effective method of safety stopping, new to the rubber industry, namely, regenerative braking instead of the heretofore used dynamic braking.

A cost study of the two systems showed the adjustable-voltage system to be economically sound. In fact, a-c distribution and d-c adjustable-voltage drives proved less costly by an important margin than the common practice of d-c substation generation, d-c distribution, and constant-voltage drives.*

## Driving Equipment

Most of the basic elements of the drive are shown in the sketch, figure 2. The generators are of standard shunt-wound construction, liberally rated and with a low saturation factor to enhance regen-

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* It should be noted that this statement refers to a new plant in which economic questions are not influenced by existing equipment. With a constant-voltage system already established the same economic balance would not necessarily hold.

In the present instance, the cost of three-wire motor-generator sets, duplicated to insure continuity of service, high-voltage a-c switchgear, three-wire d-c switchgear and distribution, and constant-voltage driving motors and control were compared with that of high-voltage a-c switchgear, step-down power transformers, low-voltage a-c switchgear and distribution, and adjustable-voltage motor-generator sets, motors, and control. A two-wire constant-voltage d-c power system to take care of certain constant-voltage drives which would otherwise receive power from the main three-wire system was also included in the latter. No account was taken of possible differences in operating efficiency or improved production.

It may be of interest to note that having adopted the adjustable-voltage system, future expansion continues to be economical and, because of flexibility, is easily accomplished.

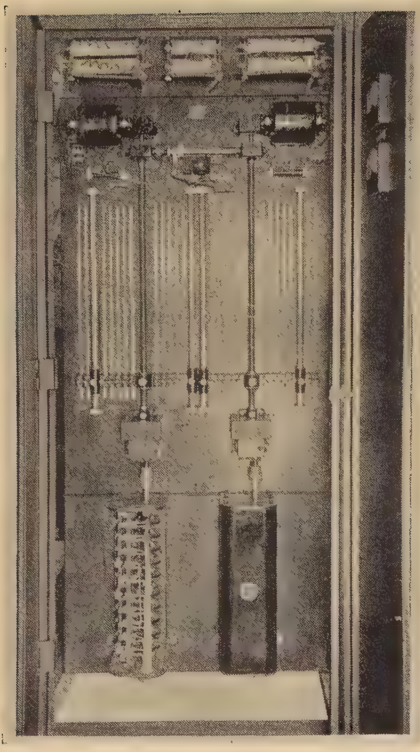


Figure 3. Motor-operated generator, calender motor, and preset speed rheostats with multiple limit switches and interconnecting clutch mechanism

erative braking and stable operation at low speeds. The exciter is compound wound and supplies all control-circuit power as well as excitation.

The motors are also shunt wound. They are selected with due regard to the fact that the adjustable-voltage drive is a constant-torque drive while the calendering operations require somewhat increased torque as speed is reduced. In the present instance full armature voltage is attained at approximately half of full production speed so that the drive is constant horsepower from full to half production speed and constant torque below half production speed. This results in a normal torque rating over the entire operating range that is amply above that required by the load. Due regard also is given to the relatively greater armature resistance of the small motors in that they are selected to have sufficient capacity to prevent them from breaking down at low armature voltages from this cause.

The control equipment consists of (1) main control board on which are mounted all the control elements that are not located at the drives, (2) master control stations placed at the calenders and at the wind-up for co-ordinated but independent control of the calendering and wind-up operations, (3) an operations set-up panel, and (4) "gate"-operated speed-relation regulating rheostats placed between the several sections.

Besides the adoption of the adjustable-voltage system, the points of interest in the sketch (figure 2) are the setting up of the equipment for the required production operations, the control of production speed, the speed regulation between sections, the regenerative braking, and the wind-up equipment.

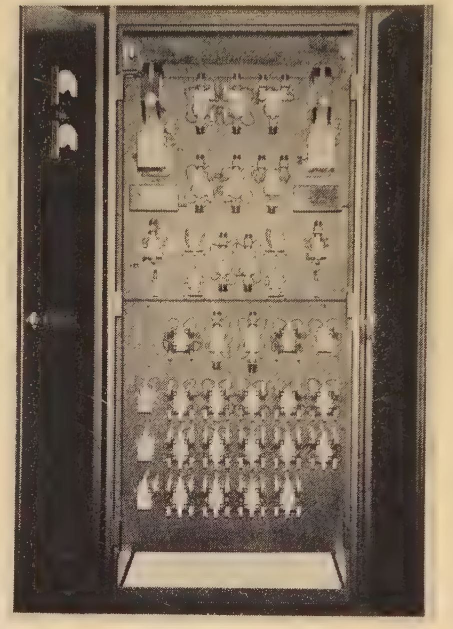


Figure 4. Typical main control panel. The relays on the bottom section control the setup operations of the rheostats, figure 3

## Setting-Up Operations

To obtain the desired operating combinations, power is supplied by two independent generators. Figure 3 shows the two generator field rheostats with compound limit switches and with a clutching mechanism between the rheostats which permits independent or unit operation. Figure 4, which is typical of the main control panels, shows the rheostat setting-up relays. Figure 5 shows the master setting-up switches available to the operator.

Referring to figure 5, two of the switches control field contactors for forward and reverse operations of the calenders. Several other switches cut individual sections in and out of service. Three switches operate in the manner shown on the index plate.

Referring to the index plate, switch number 3 is placed in position *A* to operate the two calenders and their respective sections independently. In this position switch number 3 declutches the two generator rheostats so that they can be operated independently and, as explained later sets up the two calender motors as the master motors of their respective sections.

If it is desired to operate all sections together, say with skim-coating on each calender, switches number 1 and number 2 are placed in position *A* and switch number 3 in position *B*. Under this condition, as will be recalled, the relation between fabric speed and calender motor speed for the two calenders is the same. The generator rheostats, therefore, automatically position themselves to give equal generator voltages and then clutch together. Calender number 1 becomes the master motor and calender number 2 a following motor the same as the remaining motors. All of these setting up operations are automatically accomplished with the rheostat relays and rheostat limit switches.

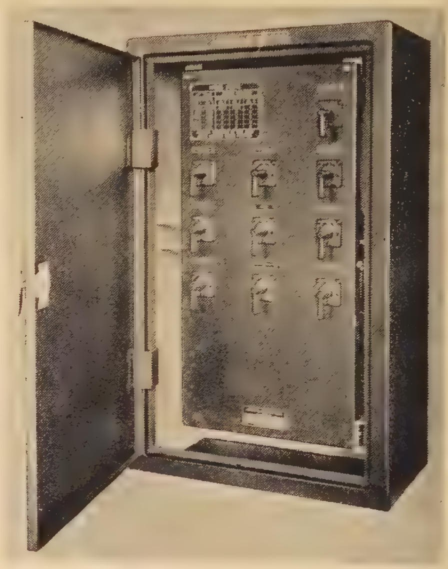


Figure 5. Master operations set-up panel. The index plate on the panel gives the switching direction for the desired production operations

Index Plate

| 24" Train Calender | | Switch Position | | |
|---|---|---|---|---|
| No. 1 | No. 2 | Switch No. 1 | Switch No. 2 | Switch No. 3 |
| Single | Single | A or B | A or B | A |
| Skim | Skim | A | A | B |
| Fric | Skim | B | A | B |
| Fric | Fric | B | B | B |
| Skim | Fric | A | B | B |

Complete train must be shut down before changing switch positions.

Instead of the skim-coating operation on both calenders assume that it is desired to skim-coat on the first calender and friction on the second. Under this condition, calender number 2 must operate faster than calender number 1, in the ratio three to two for the frictioning ratio previously assumed. The generator rheostats, therefore, position themselves before clutching so that the voltage of generator number 2 is higher than that of generator number 1 in the ratio three to two.

## Control of Production Speed

Starting, stopping, and speed control of the drive are accomplished with a stop-thread-run-hold master switch and a preset-speed rheostat, figure 6. Stopping may also be accomplished from several switches located about the driven machinery.

With the master switch in the stop position, generator excitation is removed and the generator rheostats assume the minimum generator voltage position. Turning the master switch to the thread position applies field to the generators which brings the drive to minimum speed. During this operation, full field is maintained on all motors for a definite time to insure positive breakaway and starting. Turning the switch to the run position operates the generator rheostats to raise the generator voltages to full value and then to weaken the field of the master motor.

The speed to which the generator rheostats bring the drive is determined by the setting of the preset-speed rheostat. This rheostat has a companion rheostat of duplicate characteristics built into the generator rheostat units. The voltage drops across these two rheostats are balanced against each other and when they are equal, relays function to stop further travel of the generator rheostats. Thus, if the drive is stopped or slowed down, it will always return to the original production speed as determined by the setting of the preset-speed rheostat when the master switch is again turned to the run position.

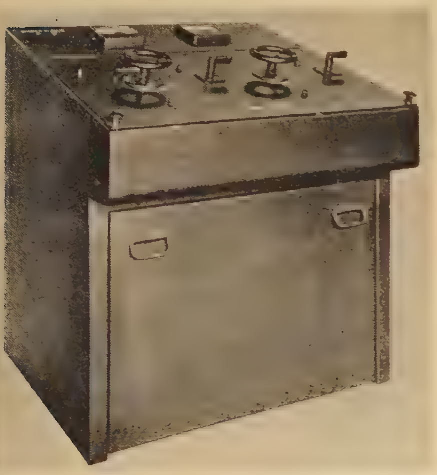


**Figure 6. Master control desk with starting and stopping control stations, speed preset rheostats, and tachometers**

At any time during the speeding up or slowing down of the drive, the speed can be maintained constant by turning the master switch to the hold position.

Upon stopping, the generator rheostats automatically assume the minimum generator voltage position. The rate of travel on the rheostats is adjustable for either direction. It is made fast on the down stroke to prevent delay in restarting after a stop.

## Speed Regulation Between Sections

Either the motor of calender number 1 or of calender number 2 is the master motor, except when the calenders are operating independently, in which case both motors are masters. Whichever motor is the master determines the speed of production. Referring again to figure 2, it will be seen that the generator rheostats are also master motor field rheostats, that is, the master motor speed is first raised by increasing armature voltage with constant motor field and then further raised by decreasing motor field with constant armature voltage. In other words, the master motor must operate at the speed corresponding to the setting of its generator-motor rheostat.

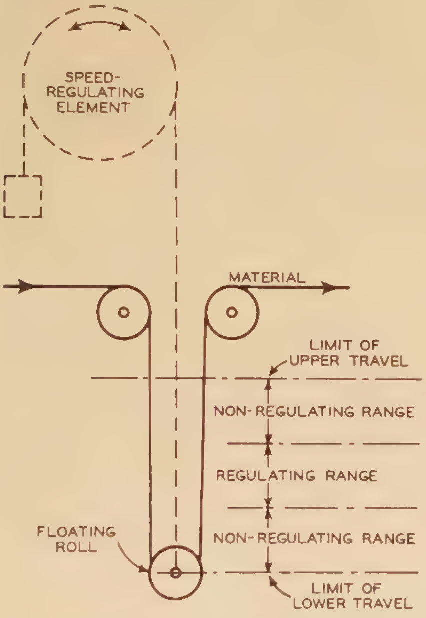
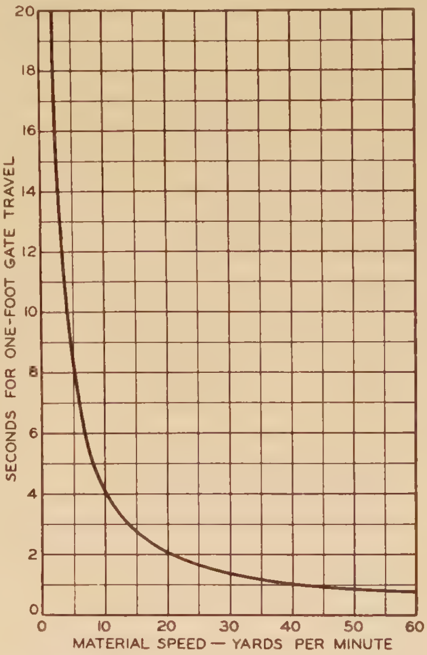


**Figure 7. Schematic diagram of typical gate or dancer roll for regulating motor speed**

All other motors are regulated to follow the speed of the master motor. This is accomplished by gates or dancer rolls which operate motor field rheostats. This form of regulation has been used for many years, particularly in the rubber and textile industries. It is discussed briefly here to show how well it works in connection with the adjustable-voltage drive and particularly where such a drive is operating in conjunction with speed control by motor field.

Figure 7 schematically illustrates a typical gate. Within its stops, the center roll is free to move up and down and in this travel it actuates the speed control element, in this case the field rheostat of the controlled motor. If the motor delivering material to the gate delivers ma-



| Yards Output | Per Cent Difference 5 | 10 | 15 | 25 | 35 | 50 | 75 | 100 |
|---|---|---|---|---|---|---|---|---|
| 60 | 3 | 6 | 9 | 15 | 21 | 30 | 45 | 60 |
| 55 | 2.7 | 5.5 | 8.2 | 13.7 | 19.2 | 27 | 41 | 55 |
| 50 | 2.5 | 5 | 7.5 | 12.5 | 17.5 | 25 | 37 | 50 |
| 45 | 2.2 | 4.5 | 6.7 | 11.2 | 15.7 | 22 | 33 | 45 |
| 40 | 2 | 4 | 6 | 10 | 14 | 20 | 30 | 40 |
| 35 | | 3.5 | 5.2 | 8.7 | 12.2 | 17.5 | 26 | 35 |
| 30 | | 3 | 4.5 | 7.5 | 10.5 | 15 | 22 | 30 |
| 25 | | 2.5 | 3.7 | 6.2 | 8.7 | 12.5 | 18.7 | 25 |
| 20 | | 2 | 3 | 5 | 7 | 10 | 15 | 20 |
| 15 | | | 2.2 | 3.7 | 5.2 | 7.5 | 11.2 | 15 |
| 10 | | | | 2.5 | 3.5 | 5 | 7.5 | 10 |
| 5 | | | | | | 2.5 | 3.7 | 5 |

**Figure 8. Tabulation and curve to illustrate the stability of gate control**

In the tabulation, for a given yards output and percentage difference in speed between sections the figure applying gives the yards output for 100 per cent difference in speed. For example: yards output 50, speed difference 10 per cent equals 5 yards output 100 per cent difference. From the curve eight seconds are required for one foot gate travel at 5 yards 100 per cent difference terial faster than the material leaves the gate the regulating roll will be lowered and conversely, if it delivers material slower, the roll will be raised. In either event, this motion is transmitted to the regulating rheostat to bring the motor speed to exactly that required.

If the material to be worked has sufficient strength to permit passing through the gate without injury, if it will stand the required flexure, and if its surface can be permitted to come in contact with rolls or similar structures this form of regulation is one of the best. It is extremely stable as indicated in figure 8 but more important its storage capacity permits momentary differences in speeds of relatively large magnitude which is valuable during starting and stopping or during momentary running disturbances. There is also no possibility of an accumulated speed change to cause an accumulation or deficiency of material between the regulated sections.

In the present drive, the gates perform three functions: (1) when the drive is not operating above full armature voltage speed, they operate merely as speed regulators to hold their respective sections in step, (2) as the master motor speed is raised into the weakened field range, they take on the additional function of following up and correspondingly weakening the fields of their associated motors, and (3) when a calender is frictioning, the gate on its companion motor automatically strengthens the field of that motor to compensate for the increased armature voltage accompanying this operation.

Between the two calenders there are two gate rheostats, one operating on each calender motor. The motor of calender number 1 is the master and the motor of calender number 2 is regulated to follow it for all operations except when frictioning on calender number 1 and skimcoating on calender number 2. For this particular operation, the motor of calender number 2 is made the master because this motor is operating below maximum generator voltage after the motor of calender number 1 has gone up to weakened field speed. The generator and motor field rheostats do not produce an operating speed strictly proportional to their travel. When the two rheostat units are offset, the differences in characteristics of the offset positions are compensated for by the gate speed-regulating rheostat. Wide range regulation of the regulated motor is more effective in the weakened-field range than in the armature-voltage range and the regulated motor is therefore set for this condition by making the motor of calender number 2 the master.

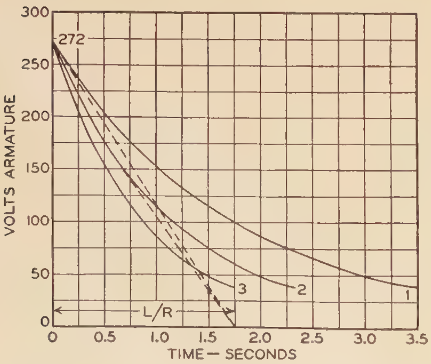


**Figure 9.** Typical field decay characteristics for 150-kw generator

For any armature voltage, inductance divided by field circuit resistance ($L/R$) is a measure of speed of field decay

## Regenerative Braking

Regenerative braking was adopted instead of the customary dynamic braking because of its greater simplicity and because it produces as quick, if not a quicker, stop than by dynamic braking. Regenerative braking as referred to here consists of opening the generator field and simultaneously establishing a generator field "suicide" circuit. Dynamic braking consists of opening the generator armature and closing the motor armatures on a resistance load.

The simplicity of regenerative braking is twofold. Since the electrical devices are operating in field instead of armature circuits, they are simpler and less bulky. Again, as regenerative braking stops are so easily accomplished, all stops can be made regenerative braking stops and it is not necessary to design the controls for two forms of stopping as is customary in the case of dynamic braking when normal stopping is a coasting stop and an emergency requires a dynamic braking stop.

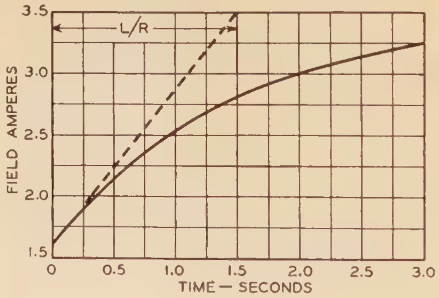


**Figure 10.** Typical field build-up characteristics for 125-horsepower motor

The regenerative braking stop also helps in another way. Since this system is applied to all stops, the several sections of the drive are brought to rest quickly and they therefore cannot depart far from their regulated positions with respect to each other. This, coupled with the fact that the adjustable-voltage drive quickly brings the sections into regulating range upon starting, results in an unusually effective speed-regulating system.

Neglecting the "suicide" circuit which is used to destroy residual and which may be considered as not affecting the results practically, the selection of generator characteristics for regenerative braking can be illustrated by the curves in figure 9. The rate of field decay is inversely proportional to the field inductance and directly proportional to the resistance of the discharge circuit. The instantaneous values of field current are a function of these two factors and the third factor—time. With these factors and the generator saturation curve, the expected performance shown in the curves can be calculated.

Having determined a reasonable inductance for curve 1, faster curves such as 2 and 3 can be obtained by increasing the discharge resistance. If it is decided that say 1.75 seconds is a desirable maximum rate of field decay, the control equipment can be arranged to operate on curve 1 at approximately 150 volts armature and above and on curve 2 below 150 volts.

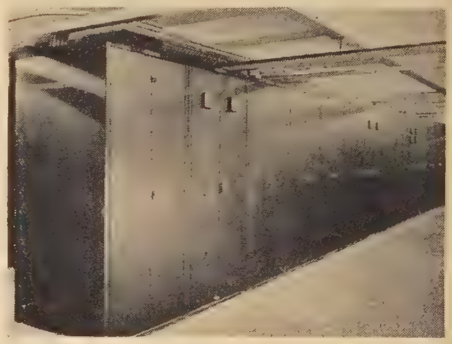


**Figure 11.** The main d-c panels for all processing operations are housed in these cubicles. The machinery is on the floor directly above

After having determined the generator characteristics the motor characteristics are checked to see that they fit into the cycle established by the generator. This is accomplished in somewhat the same manner as the calculation of the generator except that the field is rising due to application of full field for the stop and except that an additional factor, the inertia of the system,* must be taken into account. In this instance the resistance is the resistance in the motor field circuit. For practical purposes each motor may be treated independently and when so treated curves of which figure 10 is typical will result.

If the rate of motor field build-up does not differ appreciably from the rate of field decay previously calculated for the generator or in other words, if the motor becomes a generator, at approximately the same rate that the generator becomes a motor, a stable braking system may be expected. In general, if the motor does not operate over a speed range by field control greater than approximately two to one the motor will likely have inherently the desired field characteristics. For a greater speed range it may be found desirable to control the rate of motor field build-up.

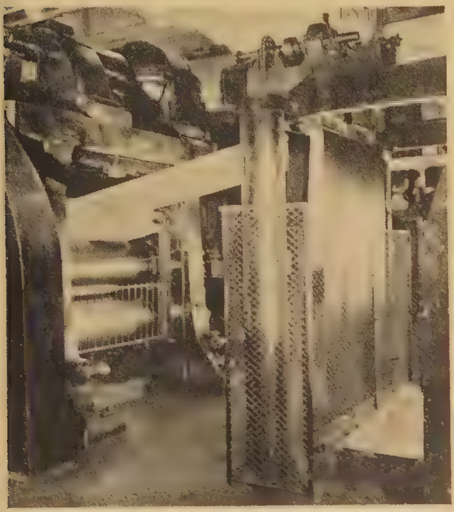


**Figure 12.** Material passing from calender number 1 into calender number 2 through the speed regulating gate. The dark surface of the material shows the rubber added by calender number 1

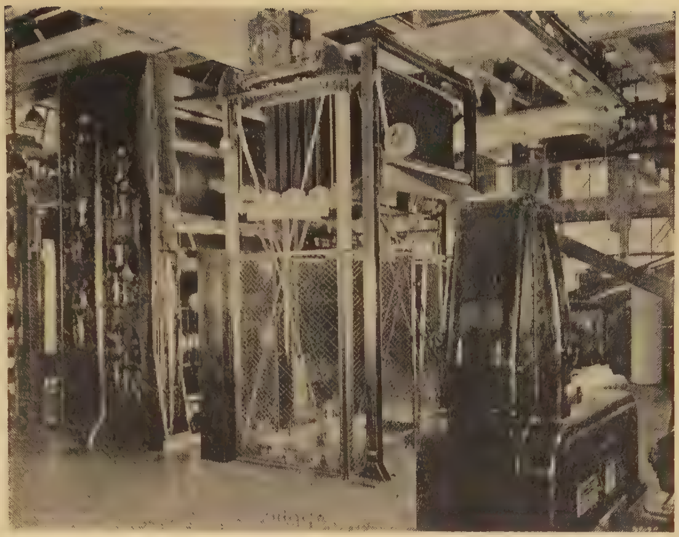


**Figure 13.** Material from calender number 2 passing through the cooler and compensator. The material at the right is going to the wind-up. The rheostat mounted on top of the compensator controls the wind-up speed

## Wind-Up Equipment

The essential differences between the wind-up operations and the operations previously described are first, that the wind-up cycle is intermittent due to the necessity of shutting down the wind-up to remove a full mandrel and insert an empty one and second, that the required operating speed range is appreciably increased because the difference in driving speed between an empty and full mandrel is added to the speed range of the continuous-production part of the system.

The matter of intermittent operation is provided for by inserting a material storage or compensator ahead of the wind-up. The compensator is shown in figure 2 from which it will be seen that if the wind-up has a production speed higher than that of the preceding part of the drive to the extent that the average production speed of the wind-up is equal to the continuous production speed of the preceding part, there will be eventually as much material taken out of the compensator as is put into it.

Intermittent operation and increased speed range of the wind-up are taken care of most effectively by again resorting to the adjustable-voltage system operating in conjunction with adjustable-speed motors. The wind-up motor is driven by an independent generator. The wind-up operator has at hand an interlocked-independent control station. In the interlocked position the wind-up starts and stops simultaneously with the preceding main drives. In the independent position, independent control of the wind-up is secured from a stop-thread-run control station.

Referring again to figure 2, it will be seen that if this control station is moved from stop to thread, full field is applied to the motor and field is applied to the generator through a generator-field threading resistor to give the armature voltage required for the desired threading speed.

Turning the control further or to the run position, transfers control from the threading resistor to the compensator-controlled rheostat. This rheostat is a combined generator and motor field rheostat designed to operate in the same manner as the combined rheostats for the calender motors. The setting of the rheostat is determined by the position of the compensator rolls from which it is operated in the same manner as the gate speed-regulating rheostats. From full to approximately half full compensator, the wind-up operates at full speed. From half full compensator to empty compensator, the speed is reduced from maximum to minimum. Limit switches are placed at the extreme compensator travels to shut down the drives should the normal operating range be exceeded.

All starts are made automatically through the threading resistor so that all slack in the equipment is taken up before the drive is thrown over to operating speed. As with the remainder of the drive, all stops for the wind-up are regenerative braking stops.

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* Ascertain if the horsepower necessary to stop within the required time is within the capacity of the motor. This should be calculated at maximum speed which is the worst condition.

$$\text{Torque} = \frac{WR^2N}{307\,t} \text{ and horsepower} = \frac{N\ \text{Torque}}{5{,}250}$$

in which $WR^2$ is the inertia of the system, $N$ is the operating speed, and $t$ the required seconds to stop.

# The Permatron—A Magnetically Controlled Industrial Tube

By W. P. OVERBECK
ASSOCIATE AIEE

THE Permatron is a new gas-filled control tube in which the initiation of a discharge may be controlled by an externally applied magnetic field. The possibility of this type of control has been recognized during the past few years,[1] but little attention has been paid to proper design or to the interesting applications of tubes built specifically for magnetic control. The present paper has been written as the result of research work which has shown that magnetic-control tubes are a reliable and useful addition to the field of electronics. The trademark "Permatron" has been chosen to indicate the use of magnetic control.

## Construction and Operation

Figure 1 shows a typical Permatron construction. In addition to the anode and cathode, which are conventional, the bulb contains a cylindrical collector electrode which surrounds the discharge path. The controlling magnetic field is applied as shown through the poles of an electromagnet located outside the bulb. Nonmagnetic materials are used for all parts of the tube which might affect the proper distribution of the magnetic field. The most practical materials are graphite, for machined parts, and 18.8 stainless steel, which has a permeability of 1.1 when properly annealed. The nickel-alloy materials used for cathodes are operated at temperatures sufficiently high to reduce their permeability.

When a positive anode voltage and a magnetic field are applied to the Permatron, electrons emitted by the cathode are deflected and strike the collector. Due to the presence of the collector, which is usually maintained at a potential close to or equal to that of the cathode, this deflection takes place in a region of weak electrostatic field intensity and the electrons are removed from the discharge path before acquiring sufficient velocity to cause ionization. If the magnetic field is removed, the electrons proceed toward the anode, gaining velocity and producing ionization. Conduction continues at a low-voltage drop between anode and cathode until the anode voltage is removed or reversed. Thus, the initiation of a heavy current discharge may be controlled by diverting electrons which represent but a microscopic portion of the same current. For each value of anode voltage, there is a critical value of magnetic field intensity above which the discharge will not start. A theory of the relationship of this critical magnetic force to anode voltage and to the pressure of the gas within the tube has been developed and shows an interesting agreement with actual results.

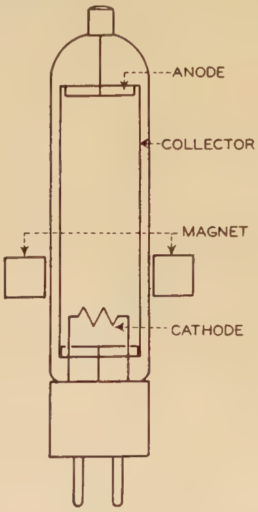

Figure 1. RM-201 Permatron

An electron in an electrostatic field and a transverse magnetic field moves in a series of cycloid paths as shown in figure 2, and in a general direction at right angles to both fields. The values of magnetic and electrostatic fields normally employed in the Permatron are such that the dimensions of the individual cycloids are small and the electrons may be considered as moving sidewise in a straight line. However, due to the presence of gas molecules, the sidewise motion is broken up by collisions between electrons and molecules. At each collision the electron may gain a little in progres in the direction of the electrostatic field. If we take, as an index of the effective sidewise motion of the electron, the number of cycloid paths in a mean free path, or average distance which an electron may travel without collision, and assume that this number must be a constant to prevent conduction in a given Permatron design, we obtain the following relation:

$$\text{magnetomotive force} = K\sqrt{EP}$$

giving the critical magnetomotive force as a function of anode voltage $E$, and gas pressure $P$. $K$ is a constant which includes proportionality factors between pressure and mean free path, magnetomotive force and magnetic field intensity, anode voltage and electrostatic field intensity, and the assumed constant ratio between mean free path and length of the cycloid paths. Figure 3 shows values of the constant $K$ (magnetomotive force/$\sqrt{EP}$) plotted against magnetomotive force for the full range of control of a mercury-vapor Permatron. The deviation from the theoretical constant value at low values of magnetomotive force corresponds to conditions under which the dimensions of the individual cycloid paths become comparable in size to the internal dimensions of the tube.

When a straight cylindrical collector such as that of figure 1 is used, the mag-

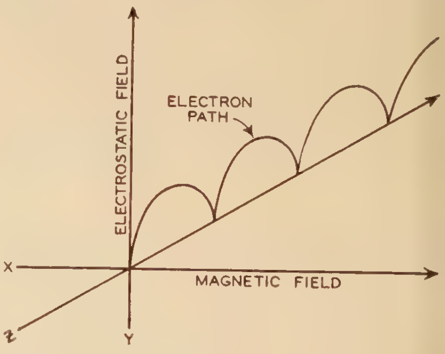

Figure 2. Path of an electron in electrostatic and transverse magnetic fields

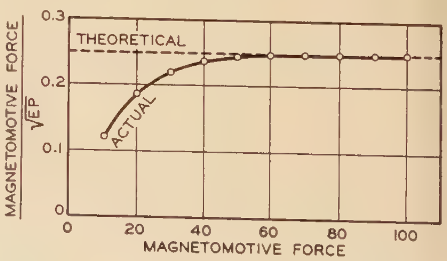

Figure 3. Comparison of Permatron theory with actual test data

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Paper number 39-20, recommended by the AIEE subcommittee on electronics, and presented at the AIEE winter convention, New York, N. Y., January 23–27, 1939. Manuscript submitted November 3, 1938; made available for preprinting December 10, 1938.

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Development of the Permatron and its methods of application is the result of co-operation of the members of the research and development department of the Raytheon Production Corporation.

[1] For all numbered references, see list at end of paper.

netic sensitivity of the Permatron increases approximately as the cube of the ratio of distance between anode and cathode to diameter of the collector. This is due partly to the resulting decrease in electrostatic field intensity in the control region and partly to the fact that a greater length of collector surface is available to catch electrons. The practical limits of sensitivity are reached when the shielding effect of the collector becomes so great as to prevent starting of the tube at reasonably low anode voltages when no magnetic field is present.

When other requirements such as the proper distribution of heat in a mercury-vapor tube must be met, a construction such as that of figure 4 is convenient. Here, the effective region of the collector is a cylindrical constriction formed by holes in a pair of graphite disks. The magnetic field is led into this region through iron armatures from a part of the bulb where location of the external magnet is most convenient. The use of two graphite disks, one above and the other below the iron poles, helps to shield the iron, which might otherwise tend to produce secondary electrons, and increases the length of the effective region. The outer cathode heat shields of this tube are made of nonmagnetic steel.

## Characteristics

There are three distinctly different types of operation obtainable with the Permatron. Characteristics are shown in figure 5 for simple magnetic control in which the collector is directly connected to the cathode. These curves indicate the variation in control characteristics caused by changes in condensed-mercury temperature in the tube of figure 4. For circuit design purposes, it is most convenient to express the magnetic field intensity in terms of ampere turns applied to an electromagnet located in the most effective position. To give an approximation of the power needed for control, the value of 300 ampere turns in figure 5 represents 2.34 watts consumed in the magnet used for obtaining data for the curves. The tube of figure 1 requires about 0.075 watts for control of its maximum allowable anode voltage. These control power requirements are small in comparison to the power which the tubes will handle. The tube shown in figure 4 will control 16 kw while that of figure 1 will control 10 watts.

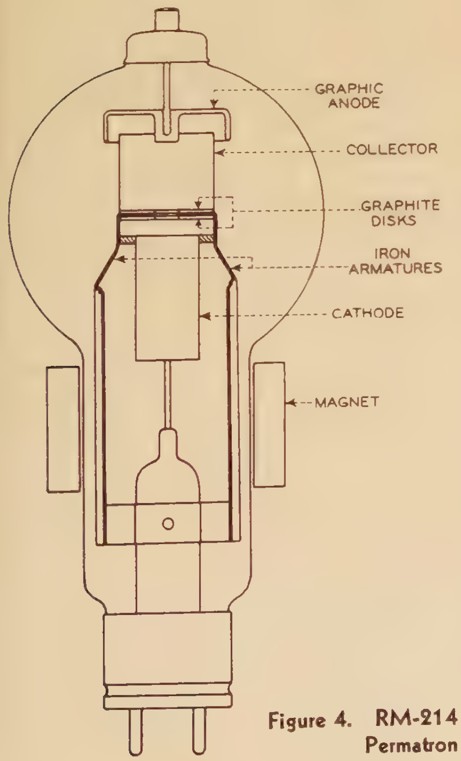


**Figure 4. RM-214 Permatron**

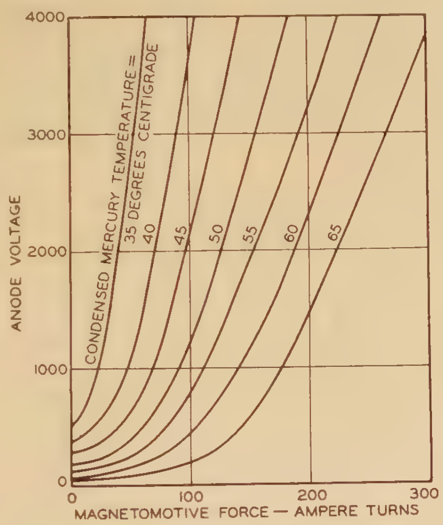


**Figure 5. Characteristics of RM-214 Permatron**

A second type of operation is that in which varying collector potentials are employed. This is similar to grid control except for the fact that the controlling effects of collector potential and magnetic field are interrelated as shown by the curves of figure 6. These particular curves indicate that the negative collector potentials and magnetic field intensity have an additive effect. This is not always true because it has been found that, in some other tube constructions, the minimum anode firing voltage may occur at a negative collector potential or at some value of magnetomotive force greater than zero. Such unusual effects are possible because the region where the magnetic field is applied may be located in a position where collector potential has a great effect on electrostatic field intensity or in a position where the electrostatic field intensity does not vary appreciably with collector potential. Also, the magnetic and electrostatic fields may be used to produce focusing effects which counteract one another.

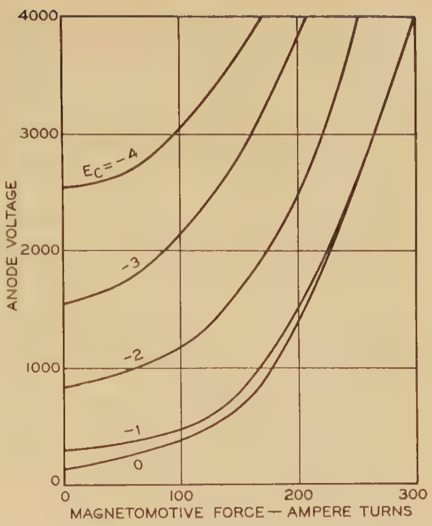


**Figure 6. RM-214 Permatron characteristics showing effect of varying collector potential**

Condensed mercury temperature = 45 degrees centigrade

The third type of operation is that in which ionization may be present in the tube without producing a discharge between anode and cathode. A Permatron such as that of figure 4 may be operated with a discharge between collector and cathode; in which case, the magnetic field may be used to prevent the discharge from spreading through the holes in the graphite disks to the anode. When the cathode-collector discharge is small, of the order of one milliampere, this has the same effect as would be obtained by moving the cathode closer to the holes in the graphite disks and produces anode control characteristics similar to those of figure 5, except that greater values of magnetomotive force are required and the anode firing voltage at zero magnetomotive force is greatly reduced. This type of operation has been used to make a tube designed for high-voltage applications more useful in circuits where low anode voltages are employed.

## Field of Application

The Permatron performs the same type of service as has been obtained from thyratrons[2] and ignitrons.[3,4] Thus, its field of application overlaps to some extent. In the same field, it has three features which are useful in certain types of applications:

1. An electromagnetic control may remain insulated from the tube and its associated

power circuit. The applications in which this feature may be useful are in the control of high-voltage circuits from a safely grounded control circuit or in circuit arrangements which normally prevent the control of two or more tubes from a common control source. An example of the former is the use of control tubes for keying the high-voltage supply of a telegraph transmitter[5] where the Permatron may be used as a high-voltage rectifier and periodically blocked by a control magnet operated at low voltage from an ordinary telegraph key. An example of the latter is in welding control circuits[6,7] where the control tubes are connected with the anode of one tube tied to the cathode of the other and vice versa. The use of the Permatron for this type of application avoids the need of connecting the control circuit to the cathode of either tube.

2. Control of the Permatron is independent of the polarity of the magnetic field. In cases such as the welding circuit mentioned above or in full-wave rectifier circuits where the anode voltages of two tubes are 180 degrees out of phase, the voltages applied to their control magnets may have the same polarity or a single magnet may be used to control both tubes.

3. The Permatron produces unusual phase-shift control characteristics which are described in detail later.

The usefulness of the Permatron extends to a new field of applications due to other factors which are listed below:

1. New combinations with moving machinery are possible because the Permatron may be controlled by moving permanent magnets. An example of this is in the problem of elevator leveling or control where permanent magnets might be mounted on the cage to operate Permatrons at various levels in the shaft.

2. A wider application to communication circuits or measuring instruments is possible because of the lack of reaction between the tube and control magnet. The control impedance remains the same and is linear whether the tube is conducting or not. Thus, the Permatron may be operated directly from a transmission line without danger of reflection or may be operated from carefully balanced measuring circuits without danger to instruments.

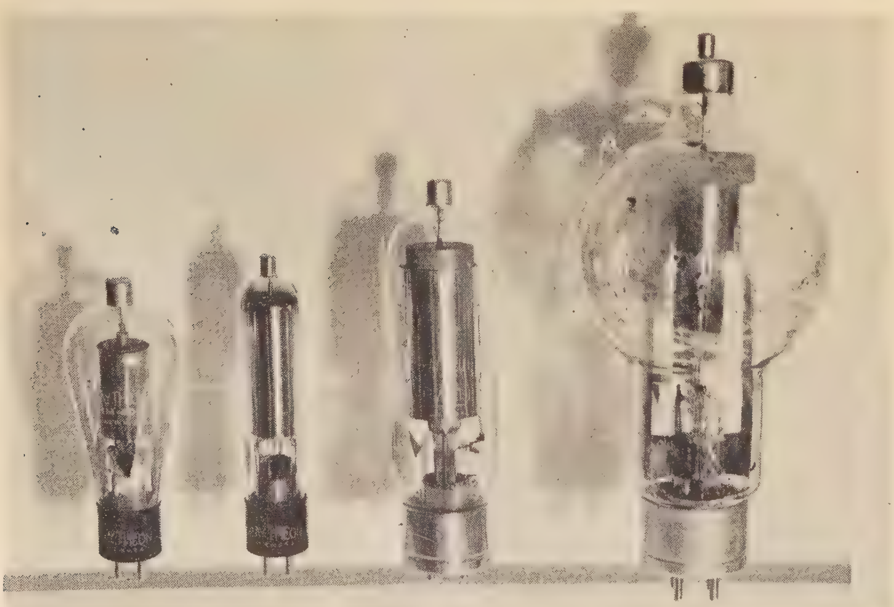
3. Operation of the control from extremely low voltages is possible, although heavy control currents are required. As an example, the tube illustrated in figure 1 can be controlled by a voltage lower than six microvolts when a single-turn control magnet is used.

Most of the development of Permatrons has been confined to the small tubes and medium power industrial tubes illustrated in figure 7. The ratings of the tubes range from an average current of 0.1 to 8 amperes and up to 3,500 volts. There is, however, no factor which prevents application of the same principles to tubes of higher voltage and current ratings. Work on such tubes is proceeding with the object of investigating the possibility of extending, through magnetic control, the present limits of both high-voltage and heavy-current gas-filled tubes.

## Control Circuits and Methods of Application

Figure 8 illustrates the analysis of a-c operation. For each point on the positive half cycle of anode voltage, there is a critical value of magnetomotive force which will prevent conduction and which may be either positive or negative. These values of magnetomotive force which may be obtained from curves similar to those in figure 5, form a closed oval as shown by the dotted line. If an alternating magnetomotive force is applied to the control magnet, conduction starts in each cycle at the point where the magnetomotive force wave intercepts the critical oval and continues until the anode voltage becomes negative. This period of conduction, indicated by the shaded portion of the diagram, may be increased or decreased by varying the phase relation between anode voltage and magnetomotive force.

**Figure 7. Experimental Permatrons**



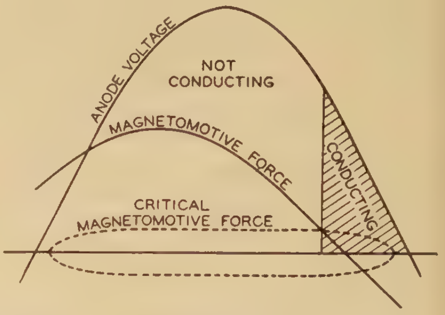


**Figure 8. Oscillographic analysis of a-c operation**

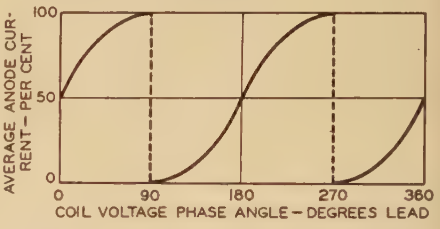


**Figure 9. Output characteristic of Permatron with phase-shift control**

Phase shift control of this type has been described in connection with other types of control tubes[2] so it is possible to limit the present discussion to unusual results obtained from its use with Permatrons.

It may be seen, from inspection of figure 8, that the instant of starting, or firing angle, in each cycle is limited to the relatively short period that the magnetomotive force wave is passing through the critical oval. If the tube fails to start during this period as a result of some external condition such as the anode circuit being open, it cannot start later in the cycle. If the amplitude of the magnetomotive force wave is increased, this available starting period may be made shorter. An effect of this sort is very useful in applications such as resistance welding and motor control where an accurately set firing angle is required. It avoids the need of special peaking transformers in the control circuit.

As the phase angle between anode voltage and control-magnet voltage changes, the average current through the Permatron varies as shown in figure 9. The anode current variation is repeated every 180 degrees, and the discontinuous

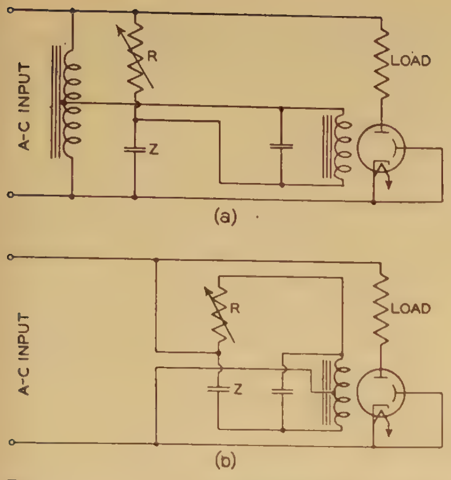


**Figure 10. Permatron phase-shifting circuits**

points occur at the power-factor angle of the control magnet which is usually close to 90 degrees. In welding or in full-wave rectifier circuits where tubes are connected with their anode voltages 180 degrees out of phase, the two control-magnet voltages may be in phase or a single magnet may be used to control both tubes.

Two circuits which may be used for phase-shift control of the Permatron are shown in figure 10. The first (*a*) is an adaptation of the conventional type of phase-shift circuit. The reactive element *Z* may be either a capacitor or an inductor. When the resistor *R* is varied from zero to infinity, the phase angle of the control magnet varies from zero to 180 degrees with respect to the anode voltage. A capacitor whose capacitance resonates with the control-magnet inductance at the power-line frequency may be connected in parallel with the control magnet to reduce the current drawn from the phase-shift circuit. The second circuit (*b*) avoids the need of a center-tapped control-voltage source by using a center-tap on the control magnet. This circuit is easy to understand when it is realized that it is the same as the one above except that the connections are reversed. The magnet takes the place of the center-tapped source and the terminals which would normally be the output of the phase-shift circuit are connected to the power lines. The impedance *Z* and the mean value of the resistor *R* should be large compared to the impedance between the center-tap of the control magnet and the two outer terminals when the latter are short-circuited and should be small compared to open-circuit impedance between the outer ends of the control magnet. Use of a resonating capacitor across the magnet makes the latter value larger.

In automatic control circuits, it is usually preferable to obtain phase-shift control from direct current. This preference is due to the fact that such control devices often include a vacuum-tube amplifier which produces a varying d-c output. A very useful circuit for this type of control is shown in figure 11. Two coils are wound on each control magnet, one to be operated from alternating current and the other from direct current. When two tubes are used, these coils may be arranged so that the alternating voltages induced in the two d-c coils are balanced out. The same result may be accomplished with single-coil magnets if the coils are connected in a balanced bridge circuit with the alternating current applied to one pair of opposite corners and the direct current to the other corners. The oscillographic drawing below the circuit diagram shows the results obtained. Due to the balancing connection, the d-c magnetomotive force shifts the two a-c magnetomotive force waves in opposite directions. These magnetomotive force waves are illustrated as sine waves, each drawn with a solid line during the half cycle that its associated anode is positive. Since one wave shifts upward and the other downward, the firing angles of the two tubes shift in the same direction and their output currents remain balanced. If the connections to the a-c coils are reversed, the direction of shift in firing angle with a given change in d-c magnetomotive force is reversed.

A smooth control of output current of a Permatron may be obtained with moving permanent magnets by applying the same principle as the circuit of figure 11.

Although several complete circuits using Permatrons have been developed, a detailed description of all of them would require more space than could be alloted to one paper. However, the full wave rectifier circuit of figure 12 is shown in order to give an example of the combination of a few of the principles described above in a complete circuit. The control magnet system is a combination of figure 11 and figure 10 (*b*). The d-c coils are operated by an amplifier tube whose plate current is controlled by variations in output voltage of the rectifier. The phase-shift circuit of the a-c coils is adjusted to give the maximum rate of change of output voltage for a given change of current in the d-c coils and to set the mean output voltage at a value which produces the optimum performance of the amplifier tube. A resistance and capacitor time-delay circuit is used in the grid circuit of the amplifier to prevent hunting. This particular circuit is designed to give a constant output voltage regardless of input voltage or load variations. If the d-c coils are of low impedance and connected in series with the load, the rectifier may be made to have a drooping characteristic or a rising characteristic depending on the phasing of the a-c coils.

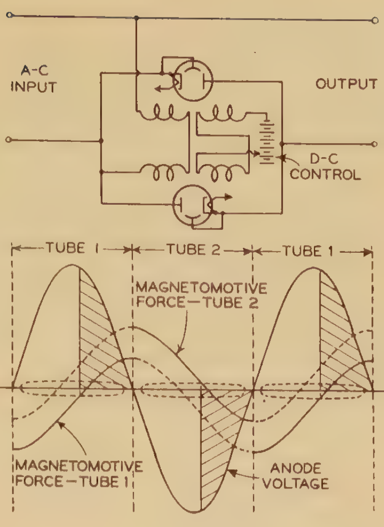


**Figure 11. Circuit diagram and analysis of combined a-c and d-c magnetic control**

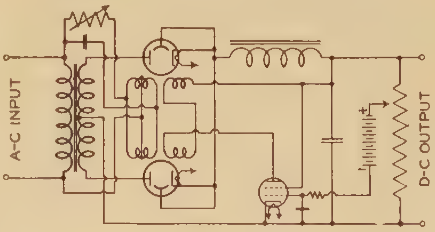


**Figure 12. Fundamental circuit diagram of Permatron-controlled rectifier**

## Conclusion

Magnetic control as described above has proved itself both reliable and efficient and, having so many useful features, it should find many industrial applications. Moreover, since it is possible to obtain both grid control and magnetic control effects in the same tube, there are many applications in which the desirable qualities of both types of control may be obtained simultaneously. In circuit combinations and in possible variations of control characteristics, the Permatron should provide a fertile field for new ideas.

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## Discussion

**S. B. Ingram** (Bell Telephone Laboratories, New York, N. Y.): Mr. Overbeck and his associates have done the industry a service in making a line of magnetically controlled gas tubes commercially available. The advantages of devices of this type have been recognized for some time as the author has pointed out in his paper. The availability of a new device, however, is always a great stimulus to its wide application and we shall now have an opportunity to see the magnetically controlled tube prove its mettle in competition with other types of gas-filled control tubes.

There is one characteristic of mercury-vapor-filled Permatrons which, I believe, will be a considerable impediment to its circuit application. This is the variability of its characteristics with condensed mercury temperature. The characteristics of the thyratron or grid-controlled gas-filled tube also vary with temperature, but extreme shifts in the characteristic take place only below condensed-mercury temperatures of about 40 degrees centigrade. In the ordinary operating temperature range from 40 degrees centigrade to 80 degrees centigrade the characteristics are relatively independent of temperature. In the Permatron, the variability extends over the whole temperature range as Mr. Overbeck's figure 5 shows and as, in fact, his theory of breakdown demands. Rare-gas-filled tubes would be free from this disadvantage although their use would necessarily be confined to low-voltage circuits. I should like to ask if any work has been done on Permatrons with rare-gas filling.

**W. P. Overbeck:** Mr. Ingram's discussion is greatly appreciated. As pointed out in the paper, our work has led to the discovery of previously unrecognized advantages of magnetic control and it is natural to expect that, with special tubes available, other engineers will be able to add important contributions. In addition to the competitive situation mentioned by Mr. Ingram, it is to be hoped that the unusual features of the Permatron will create a new field of application.

In contradiction to the theory of control which I have proposed, I believe that there is a possibility of reducing variations of characteristics with temperature. Nonvarying characteristics of the thyratron in the range of temperatures mentioned by Mr. Ingram are not true of all types. For example, the *FG*-43 and *KU*-628 show considerable variation in this range. We are thus led to the conclusion that refinements of design are responsible for the improved characteristics of types such as the *FG*-29. A similar refinement in design of the Permatron would be such that tube construction, rather than vapor pressure, would determine the effectiveness of magnetic deflection. On the other hand, it should be noted that in an experimental industrial installation, mercury-vapor Permatrons have operated over 5,000 hours without difficulty from characteristic variations. This is, of course, due to proper circuit design.

Considerable work has been done on Permatrons with rare-gas filling. The two tubes shown in the center of figure 7 are made with argon gas. This removes variation of characteristics with ambient temperature.

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# Secondary Versus Primary Capacitors

By F. M. STARR
MEMBER AIEE

**Synopsis:** Secondary capacitors cost more than primary capacitors but they offer some additional benefits which may offset the additional costs. There are presented herein the results of a comprehensive economic study covering a wide variety of circuit and load conditions on both network and radial distribution systems to establish within reasonable limits the probable field of application of the secondary capacitor.

From the results of the study it appears that secondary capacitors can be justified in practically all cases on secondary networks but have a limited application on primary radial distribution systems.

During the past two years shunt capacitors have been applied to distribution systems in increasing quantities. Continual increases in reactive loads due to refrigerators, air conditioning, fans, and other small motor loads have had their destructive effects and corrective measures have more than ever become necessary.

Reactive amperes originate at the load and they carry their destructive effect in the form of excessive voltage drops, thermal overloads, and energy losses, back to the generator. Naturally enough, corrective measures to affect the maximum benefits should be located as close to the load or source of reactive as possible. Capacitors lend themselves particularly well as corrective devices to obtain maximum benefits because they can be obtained in small increments of capacity and may be applied in proper sizes close to the load.

From the viewpoint of maximum benefits, therefore, a small capacitor at each meter box would appear to offer the ideal correction. On the other hand, from the viewpoint of maximum benefits commensurate with maximum economy, the relative costs of capacitor correction applied at various points in the distribution system must be factored.

The cost of capacitors varies principally with the size of the individual unit and with the voltage rating of the unit. At the present stage of the art, design and manufacturing limitations are such that the capacitor having the lowest cost per kilovolt-ampere is a 10- or 15-kva unit having a voltage rating of 2,300 or 4,000 volts. This, of course, means that the lowest cost correction is that which can be applied to the primary feeder. The difference in cost between primary and secondary capacitors is quite substantial (see figure 3) and it probably is for this reason that practically all capacitors which have been applied by utilities for reactive correction have been primary-feeder capacitors.*

Although secondary capacitors cost more, they do offer some additional advantages over primary capacitors. Consider for a moment what these additional advantages consist of:

## Comparative Benefits of Secondary Versus Primary Capacitors

The elimination of reactive kilovolt-amperes from a system releases system

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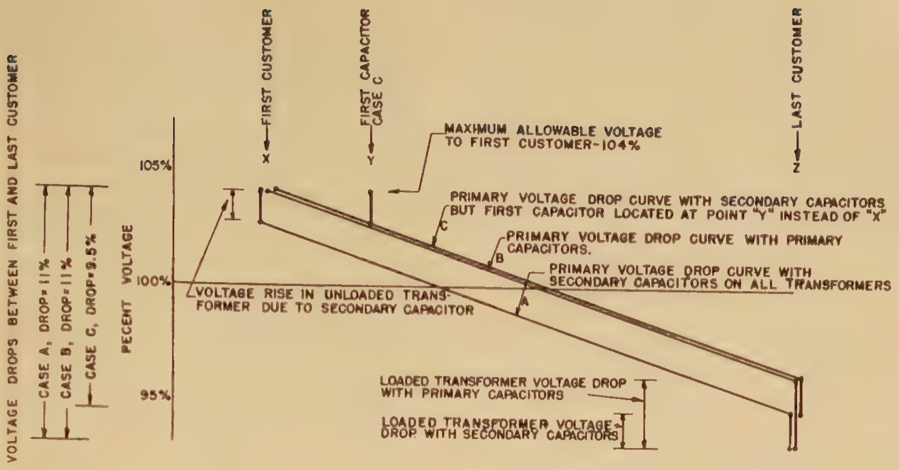
F. M. Starr is a member of the central station engineering staff of the General Electric Company, Schenectady, N. Y.

The author wishes to acknowledge here the large amount of work by T. F. Skinner in making all of the calculations and preparing all of the curves used in this paper and also the contribution of O. B. Falls in preparation of the manuscript.

* Capacitors applied by industrials, of course, are necessarily low-voltage capacitors since the utilization voltage is in most cases the only voltage available in an industrial plant.

**Figure 1 (right)**

These curves show that secondary capacitors do not give any additional reduction in voltage drop between first and last customer if all transformers are equipped with the secondary units. To gain additional reduction in voltage drop, the secondary capacitor installations should be confined to the section of line between *Y* and *Z* above. Point *Y* is that point at which the primary feeder line drop is equal to the voltage rise in an unloaded transformer due to a secondary capacitor. In the above curves, it is assumed that the first transformer may be unloaded at peak feeder load



capacity in one or both of two ways. Correction of reactive kilovolt-amperes reduces voltage drop and it also reduces net kilovolt-amperes, so depending on whether voltage drop or thermal capacity is the limiting factor, the value of released system capacity will be calculated in one of two ways.

The kilowatt carrying capacity of overhead primary feeders is practically always limited by voltage drop in the feeder so the advantage of the capacitor in releasing feeder capacity is measured as a direct function of the degree of re-

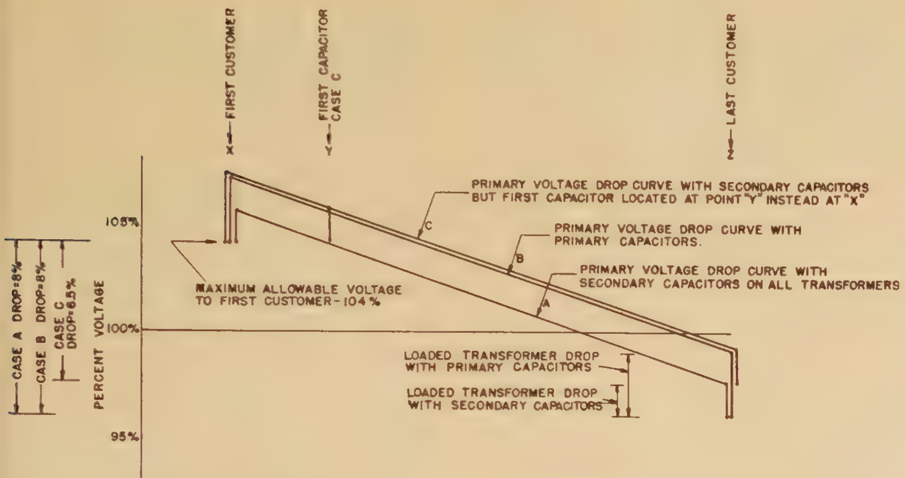


**Figure 2 (above)**

A similar comparison is made in the above curves as in figure 1 except that it is assumed here that all transformers will be loaded at peak feeder load. In this case, however, it is still true that secondary capacitors do not give additional reduction in voltage drop over primary capacitors unless they are confined to that section of the feeder between points *Y* and *Z*. For either of the conditions assumed in figures 1 or 2 it is necessary properly to set the line-drop compensator to obtain the indicated results

**Figure 3 (below)**

These curves show the relative costs of primary and secondary capacitors. The cost per kilovolt-ampere of primary capacitors is about constant since they are always multiples of 10- or 15-kva units. In this study primary 4-kv capacitors had a fixed installed cost of \$7.55 per kilovolt-ampere and 13.8-kv capacitors had a fixed installed cost of \$12.60 per kilovolt-ampere. The installed cost of secondary capacitors varies considerably as noted above. On secondary networks, however, the cost was fixed at \$22.40 per kilovolt-ampere since these were all multiples of 5-kva units

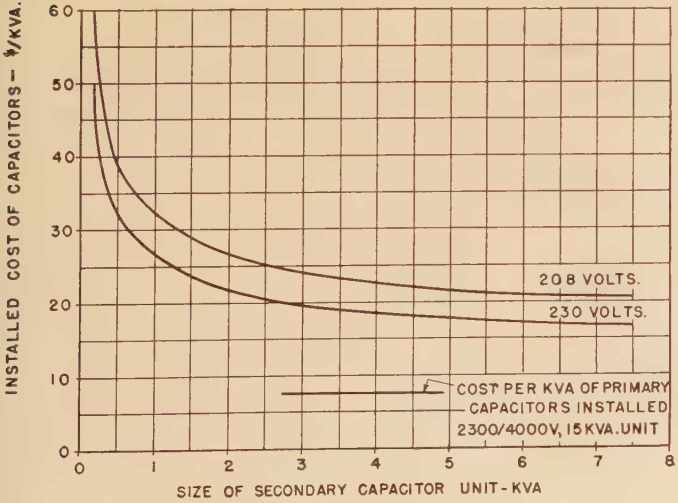
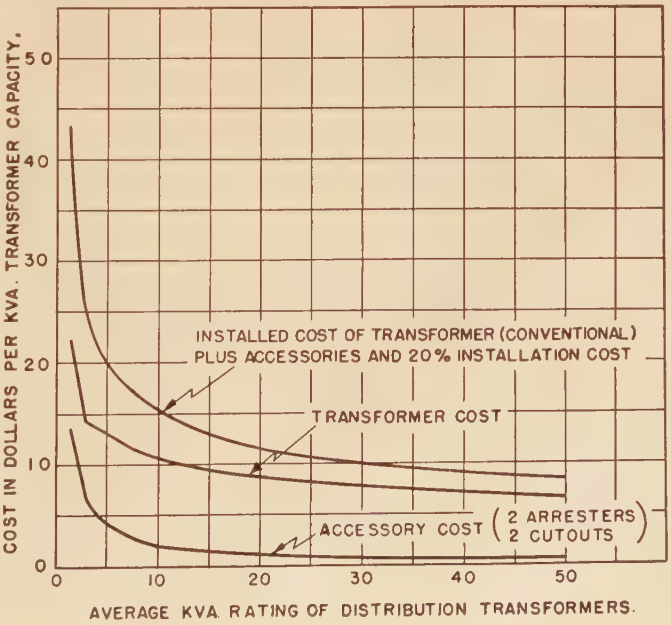


**Figure 4**

The curves below summarize the unit distribution transformer costs for the conventional type of transformer on overhead lines using two lightning arresters and two fuse cutouts, as used in this study



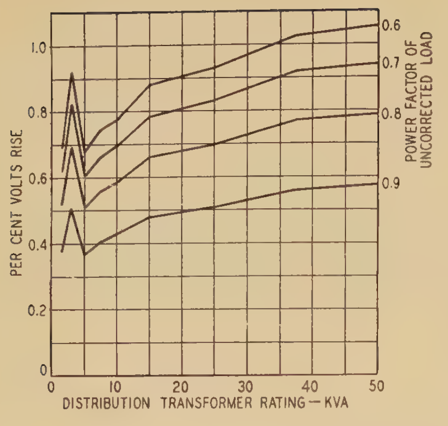


Figure 5

These curves show the amount of voltage rise which secondary capacitors produce in the distribution transformers on overhead lines. It is assumed here that the feeder power factor is corrected to unity and that the ratio of total transformer kilovolt-amperes to feeder kilovolt-ampere demand is two

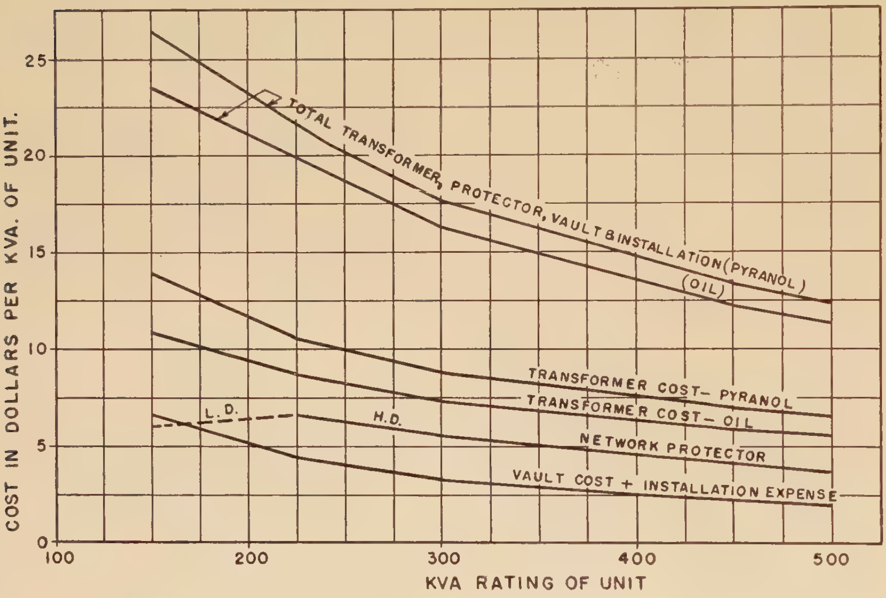


Figure 6

This group of curves shows the installed cost of secondary network transformer vaults for both oil- and Pyranol-filled transformers. Only the oil-filled transformer costs were used in making this study

duction of voltage drop on the feeder. On the other hand, the limiting factor on a transformer is its thermal capacity, so the advantage of the capacitor in releasing transformer capacity is measured as a direct function of the reduction in net kilovolt-ampere demand.

Thus, now considering the comparative merits of secondary capacitors over primary capacitors, we find that the secondary capacitor releases a certain amount of distribution transformer capacity (thermally), which the primary capacitor does not do. In addition to this, the secondary capacitor effects an additional voltage rise through the transformer by virtue of the transformer reactance. This voltage rise, when coordinated with the regulating equipment, in effect, augments the primary feeder capacity, provided it can be obtained fairly equally on all distribution transformers, since it contributes to the net reduction in voltage drop between the first and last customer on the feeder (see detailed analysis hereinafter).

So we find that a given kilovolt-amperes of secondary capacitors provided they are properly distributed, may add an additional increment of primary feeder capacity and releases a certain amount of distribution transformer capacity above and over what the same kilovolt-amperes in primary capacitors can offer.

The economic problem is to determine if this additional benefit is or is not offset by the greater cost of secondary capacitors. Actually, there are two general cases to consider—one where the secondary capacitor is located on overhead lines and the other where it is located on underground secondary networks. These will be treated separately.

If secondary capacitors have been applied in such a way that the average voltage level is higher than could be obtained with primary capacitors there will probably result an increase in revenue which may properly be considered an additional benefit. Although most engineers agree that there will be some increase in revenue with a higher voltage level, there is some difference in opinion as to the amount of increase. In the economic comparison of this study the additional revenue has been evaluated by a method acceptable to most engineers and the results have been prepared alternatively considering the additional revenue as a benefit and ignoring it. The details are given in the appendix.

## Important Factors to Consider in Comparing Primary and Secondary Capacitors

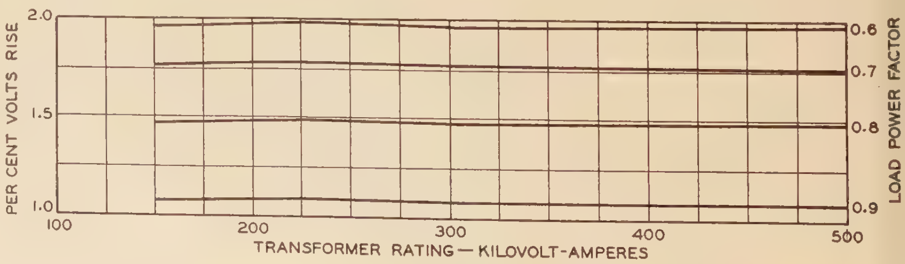
A primary capacitor releases feeder kilowatt capacity because it reduces the drop between the first and last customer. Unless secondary capacitors further reduce this drop they will not contribute additional kilowatt line capacity. Actually if every distribution transformer is equipped with a secondary capacitor the voltage drop between the first and last customer is not affected. This is illustrated schematically in figures 1 and 2, where voltage drops are plotted with both primary and secondary capacitors and considering alternatively that the first transformer may or may not be loaded at peak feeder load. It is assumed (arbitrarily) in these diagrams that each distribution transformer has $2^1/_2$ per cent voltage drop when fully loaded and $1^1/_2$ per cent rise when equipped with secondary capacitors.

On most feeders the allowable voltage to the first customer (in this case assumed to be 104 per cent) determines the amount of boost permitted the feeder regulators at peak load. If a voltage rise of 1.5 per

Figure 7

These curves are similar to those of figure 5 except they apply to secondary network transformers rather than to overhead-line installations. They show voltage rise produced in the transformer by secondary capacitors

Network transformers, 13.8 kv—120/208



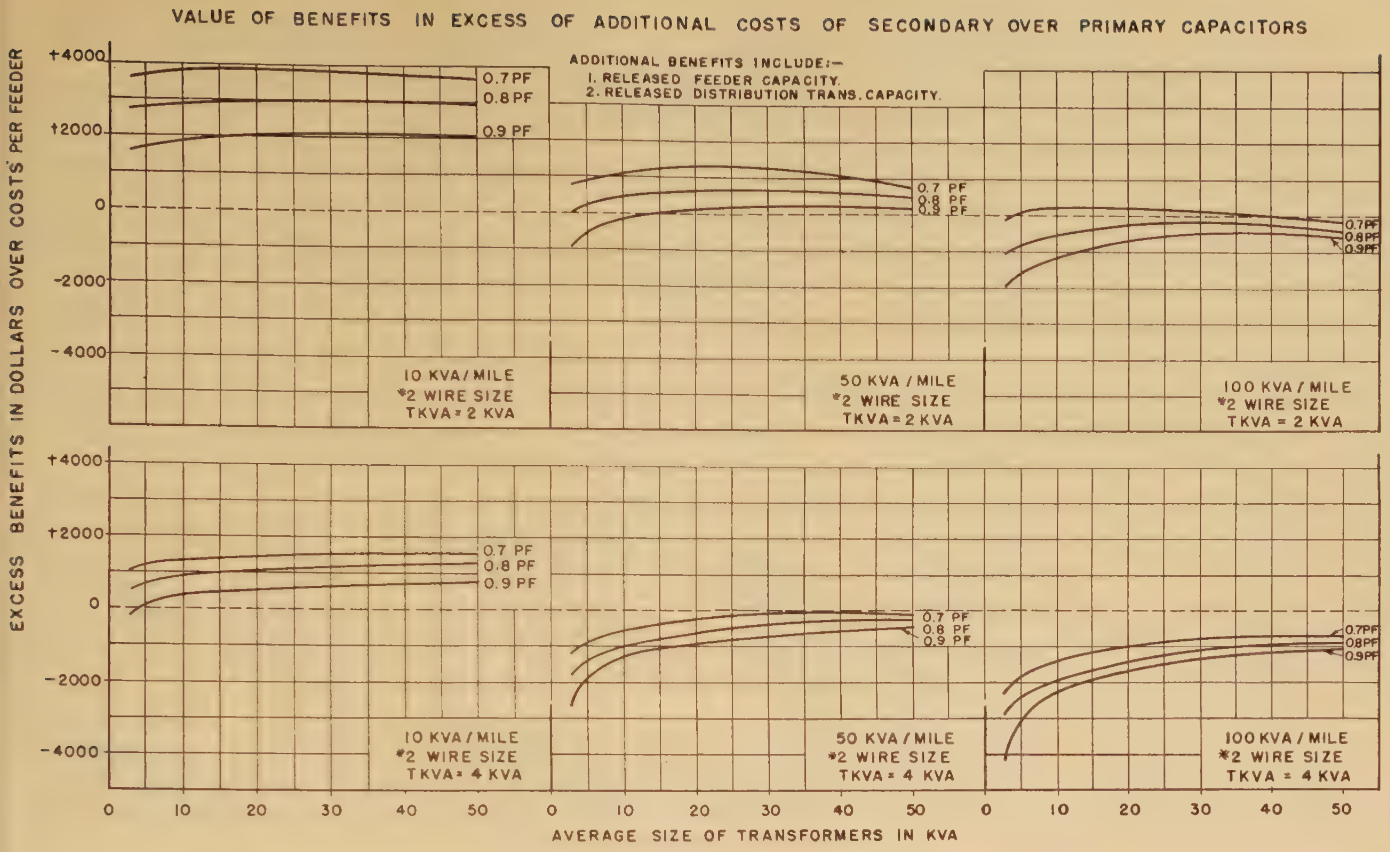


**Figure 8**

Here are plotted the values of additional benefits over costs of secondary over primary capacitors for overhead lines of a rather low load density—that is, 10, 15, and 100 kva per mile. The dollar values are total capitalized benefits in excess of or less than additional costs of secondary over primary capacitors per feeder. In all cases, any specific set of data plotted here applies to a feeder having such a length and loading as to give exactly 10 per cent voltage drop at peak load

The additional benefits tabulated here include:

1. Released feeder capacity
2. Released distribution transformer capacity

The ratio of transformer kilovolt-amperes to feeder kilovolt-ampere diversified demand was assumed alternatively two and four. The power factors assumed were 0.7, 0.8, and 0.9. The average size of distribution transformers ranged from 5 to 50 kva

It may be noted that for the conditions considered here the secondary capacitors cannot be justified except at the light load densities and low power factors

cent is introduced in each transformer by means of secondary capacitors, in effect the voltage level of the whole feeder has been raised 1.5 per cent; and to avoid giving the first customer 1.5 per cent overvoltage it is necessary to readjust to the regulator to give 1.5 per cent less voltage which leaves the feeder with exactly the same voltage to all customers as before the secondary capacitors were applied. Thus equipping all transformers with their proportionate amount of secondary capacitor correction does not result in any increase in kilowatt feeder capacity over that which can be obtained with the same kilovolt-amperes in primary capacitors.

However, if the secondary capacitors are not applied proportionately to all transformers but only to those between points *Y* and *Z* in figures 1 and 2 (point *Y* is that point at which the feeder voltage drop at peak load is equal to the voltage rise produced in the transformer by the capacitor), there will result in effect a reduction in the voltage drop between the first and last customer, in this case 1.5 per cent, and a corresponding increase in kilowatt capacity of the feeder.

In figures 1 and 2 there is illustrated rather simply the comparative voltages on the primary feeder and transformer secondary for the conditions of *A*—primary capacitors uniformly distributed, *B*—secondary capacitors uniformly distributed, and *C*—secondary capacitors distributed only between points *Y* and *Z* of the feeder. In figure 1 it is assumed that the first transformer may be unloaded at peak feeder load, and in figure 2 it is assumed that all transformers will have their peaks at the same time. It may be noted that under the last assumption there is less voltage difference between first and last customer but with either assumption of transformer loading the secondary capacitors contribute exactly the same amount of improvement. Note also that the only voltage benefit obtained by applying secondary capacitors to all transformers, as indicated in curve *A*, would be a reduction in the necessary voltage range of the regulator.

Figures 1 and 2 demonstrate further that in applying secondary capacitors, careful consideration must be given to the loading of the transformers. If all transformers have their peak loads at about the same time, the results are different than if any particular transformer is unloaded during peak load on the feeder. Only by an accurate study of transformer loading can the line-drop compensator be set properly to obtain maximum benefits from the secondary capacitors and also to avoid overvoltage conditions on specific transformers.

In general the total amount of capacitor correction to be used on the secondaries of a given feeder should equal that which would be used on the primary. This is usually made equal to the average reactive kilovolt-amperes of the diversified feeder load. Any deviation from this rule, plus or minus, results in a partial sacrifice in the maximum reduction in feeder energy losses otherwise obtained.

If the capacitor correction is equal to the average feeder reactive kilovolt-amperes and a proportional amount of it is applied to the secondary of each transformer, because of diversity, the average

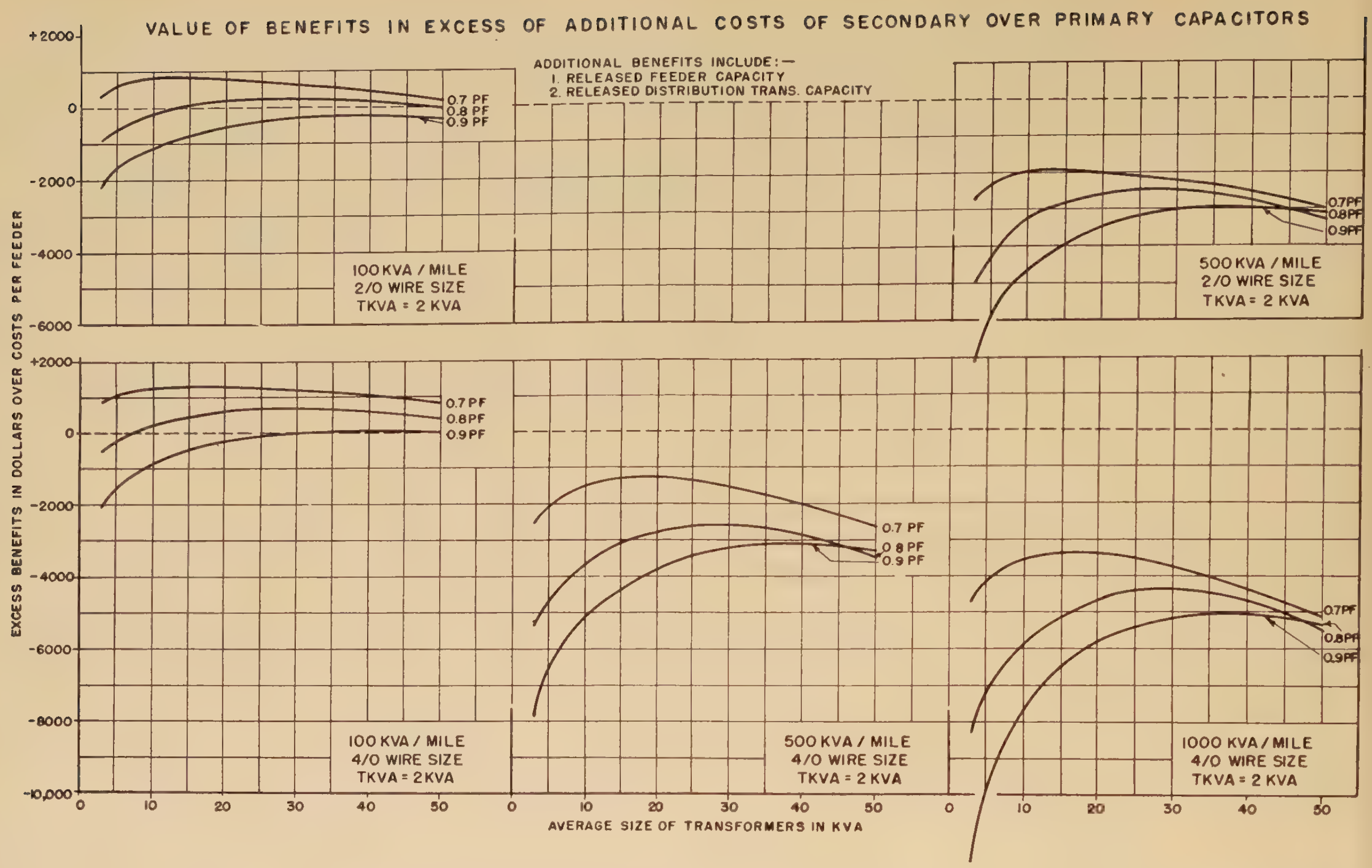


**Figure 9**

Here are plotted the values of additional benefits over cost of secondary over primary capacitors for overhead lines of somewhat higher load densities than those considered in figure 8. The load densities considered here were 100, 500, and 1,000 kva per mile. In keeping with these densities the conductor sizes assumed were 2/0 and 4/0. The dollar values are total capitalized benefits in excess of or less than additional costs of secondary over primary capacitors per feeder. In all cases any specific data plotted here applies to a feeder having such a length and loading as to give exactly 10 per cent voltage drop at peak load

Here again the additional benefits capitalized include (1) released feeder capacity, and (2) released distribution transformer capacity. The ratio of transformer kilovolt-amperes to diversified feeder demand was two. Here again the average size of distribution transformer was assumed to vary from 5 to 50 kva

Note that under these conditions secondary capacitors cannot be justified, even at the light load density of 100 kva per mile unless the power factor is fairly low

reactive load on any one transformer will only be partially corrected. Moreover, it is important to note that whereas the reactive kilovolt-amperes is reasonably constant on most feeders, this is not at all true of loads on specific transformers.

From the viewpoint of voltage control it is perhaps preferable to distribute the capacitor correction in direct proportion to transformer rating with the first installation located at a point on the feeder at which the peak-load voltage drop is equal in magnitude to the voltage rise produced in the transformer by the secondary capacitor. This procedure would insure uniform voltage rise in all transformers and also would insure the maximum additional feeder kilowatt capacity. On the other hand, with specific transformers having particularly bad power-factor or unusual load conditions, it may be desirable to concentrate more than a proportionate amount of capacitors.

It should be emphasized that unless considerable care and study is given to the application of secondary capacitors, particularly on radial secondaries, the calculated additional benefits will not be realized. In the case of banked secondaries or secondary networks the problem is not so acute, because load diversity is obtained in the network itself, which approaches that obtained in the primary feeder with radial distribution.

## Scope of Economic Analysis

To obtain a broad picture of the economic merits of secondary capacitors, it was necessary to consider a great variety of radial overhead feeders as well as secondary networks. Actually 33 overhead lines were analyzed and 24 variations in networks. The variables in circuit design and load conditions were:

Radial Overhead Feeders:

| | |
|---|---|
| Conductor sizes | numbers 2, 2/0, 4/0 |
| Load density, kilovolt-amperes per mile | 10, 50, 100, 500, 1,000 |
| Power factor | 0.7, 0.8, 0.9 |
| Average transformer size | $1^1/_2$ kva to 50 kva |
| Ratio of transformer kilovolt-amperes to total kilovolt-ampere demand | 2, 4 |

In each case the primary voltage was assumed to be 4,160 volts, since this is the voltage rating of the lowest-cost primary capacitor.

Network Systems:

| | |
|---|---|
| 13.8-kv underground cable | 4/0, 350,000 circular mils |
| Load density, kilovolt-amperes per mile | 500, 1,000, 3,000, 5,000 |
| Power factor | 0.7, 0.8, 0.9 |
| Average transformer size | 150 kva to 500 kva |
| Ratio of transformer kilovolt-amperes to total kilovolt-ampere demand | 1.5 |

The primary voltage was assumed to be 13.8 kv in each case.

In all cases the allowable primary voltage drop on 4.16-kv overhead lines

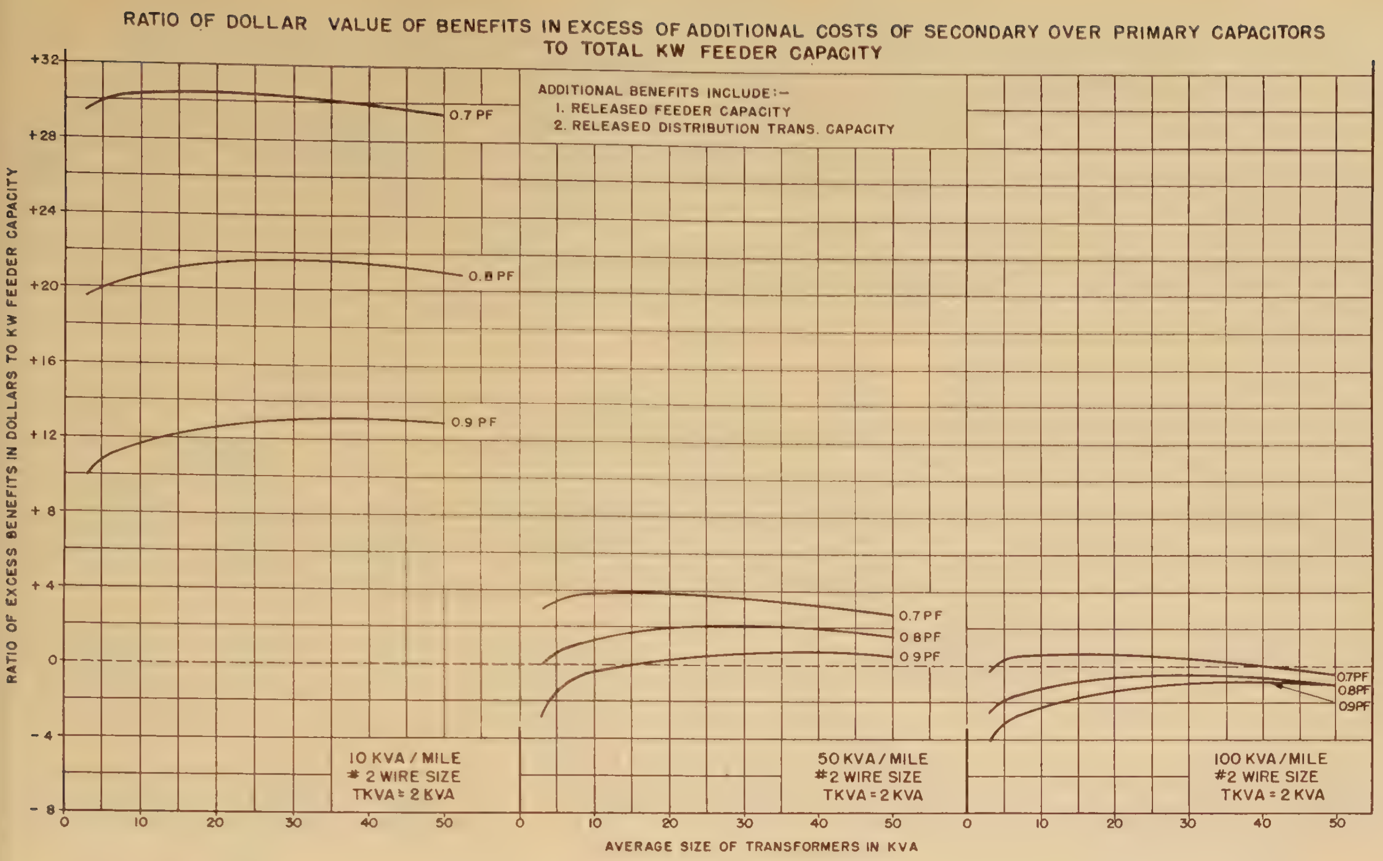


**Figure 10 (above)**

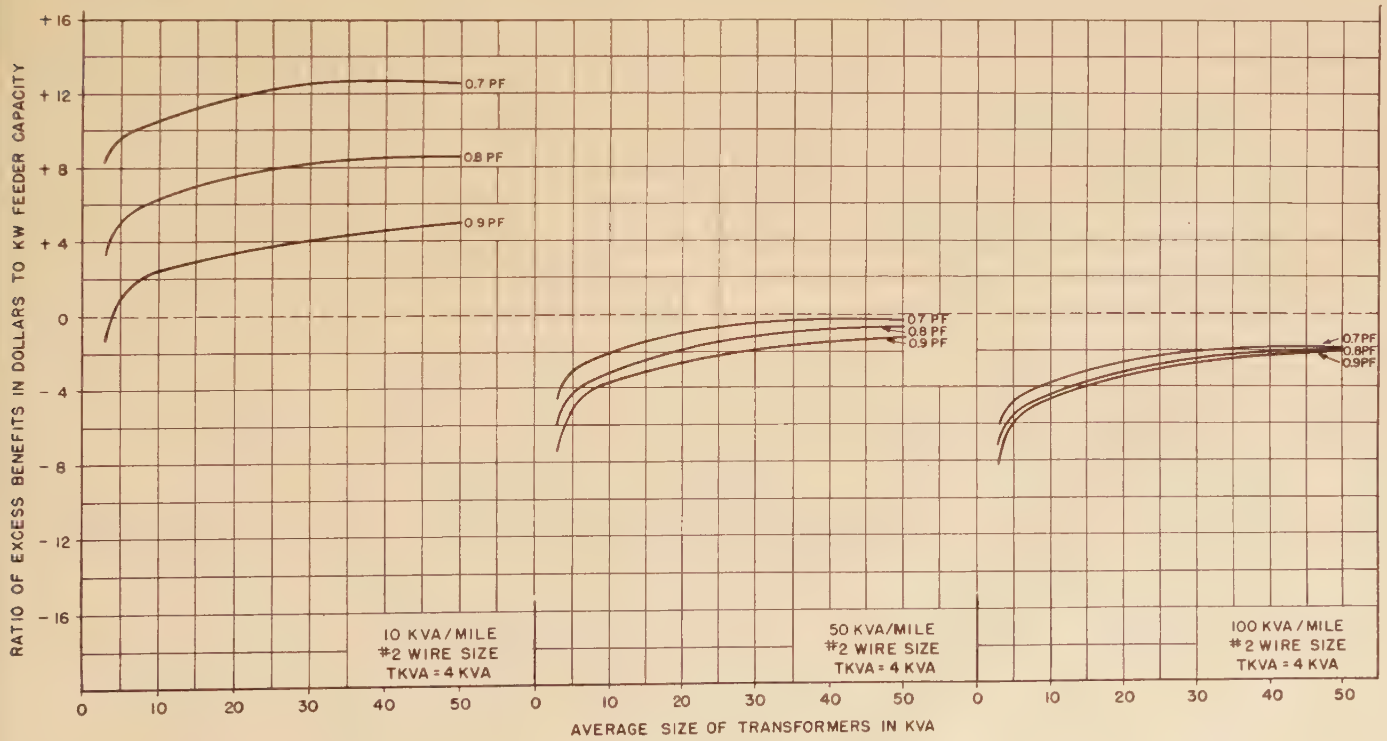
The data plotted in these curves cover similar conditions to that of figure 8 except that the additional benefits of secondary over primary capacitors have been plotted as a ratio of dollars benefit to kilowatt feeder capacity rather than dollar benefit per feeder. These data cover the set of conditions in the upper half of figure 8, that is, number 2 conductor size, load densities of 10, 50, and 100 kva per mile, and a ratio of transformer kilovolt-amperes to feeder demand of two

**Figure 11. Ratio of dollar value of benefits in excess of additional costs of secondary over primary conductors to total kilowatt feeder capacity**

These curves show the value of additional benefit of secondary over primary capacitors for the condition in figure 8, but the benefit is plotted as a ratio of dollars benefit to feeder kilowatt capacity rather than dollars benefit per feeder. These data cover the same conditions as the lower half of figure 8, that is, number 2 conductor size load densities of 10, 50, and 100 kva per mile, and a ratio of transformer kilovolt-amperes to feeder demand of four

Additional benefits include:

1. Released feeder capacity
2. Released distribution-transformer capacity



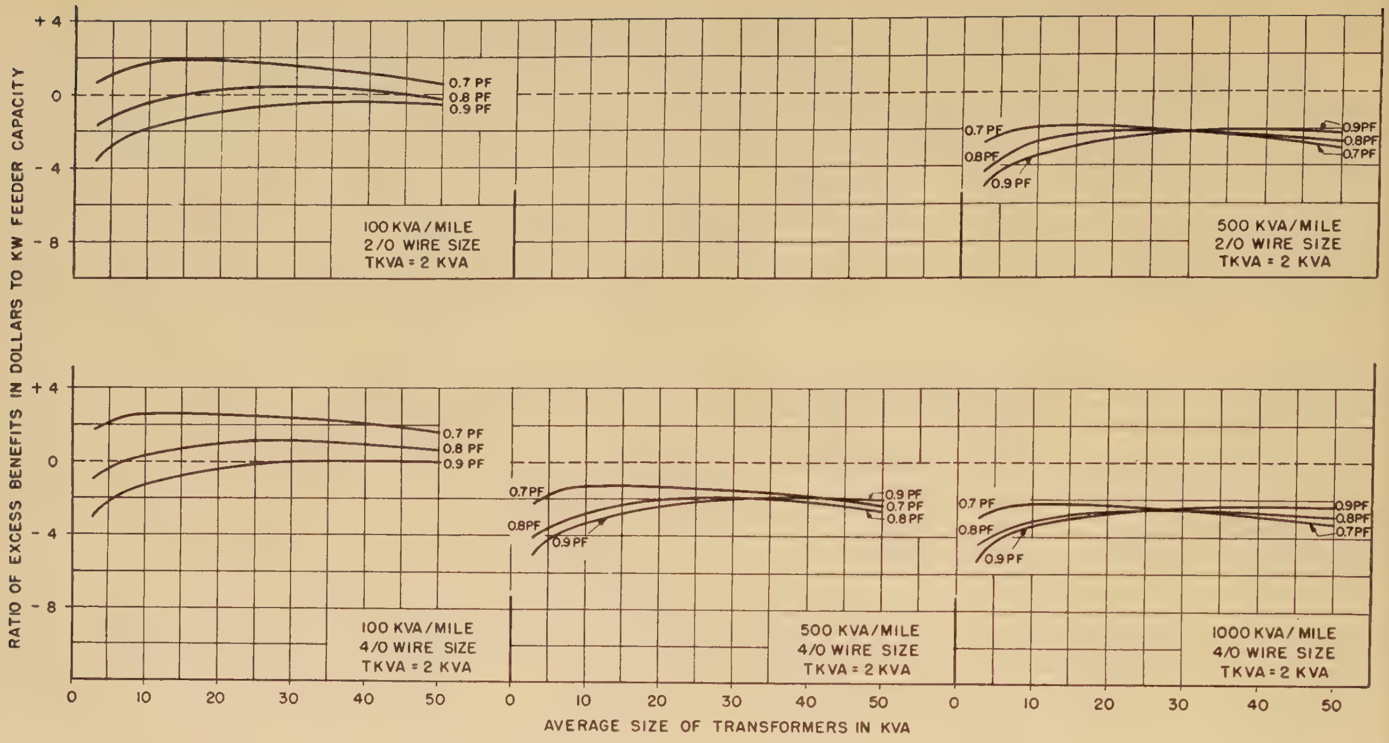


**Figure 12 (above). Ratio of dollar value of benefits in excess of additional costs of secondary over primary conductors to total kilowatt feeder capacity**

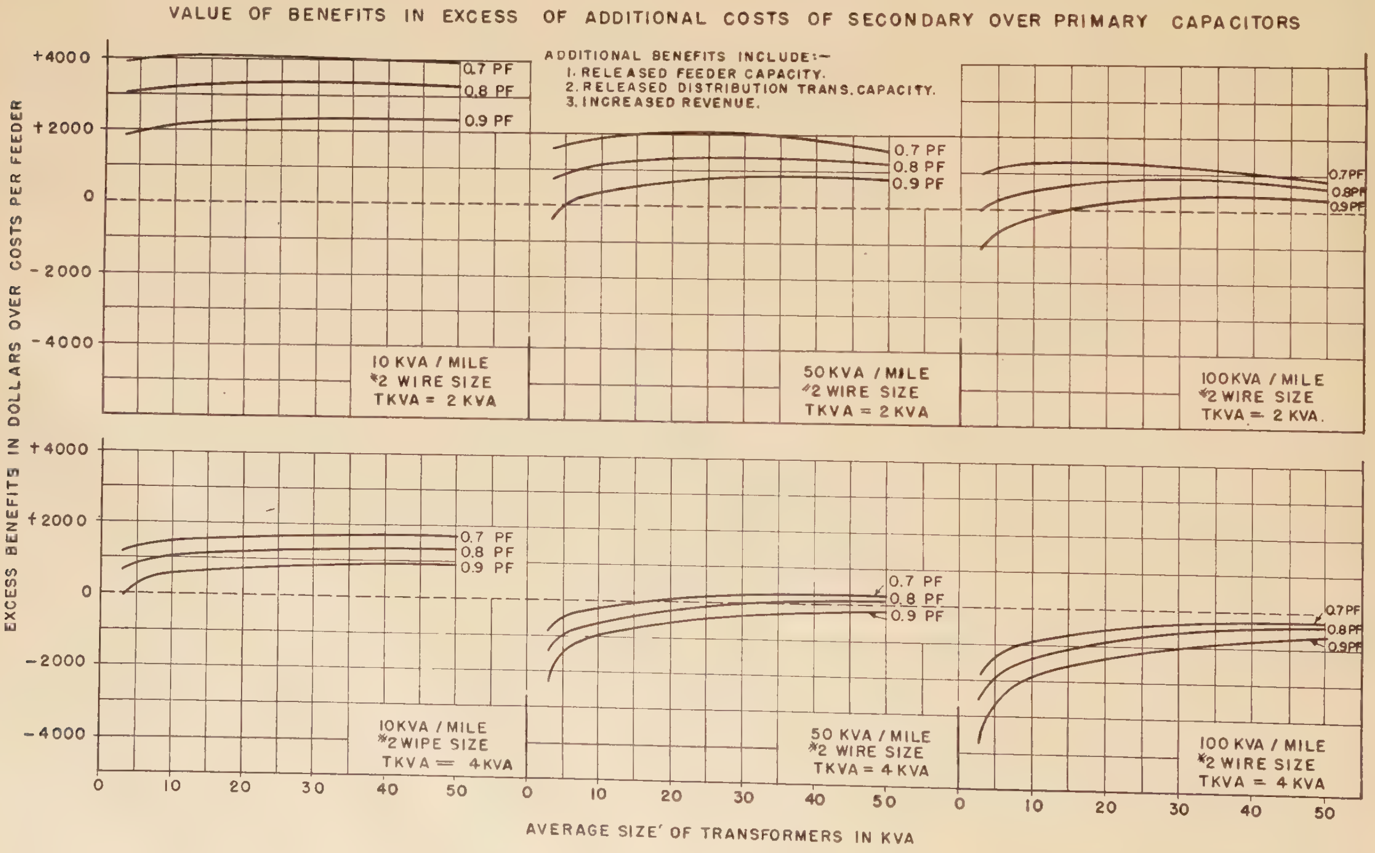
These curves cover the same conditions as those of figure 9, that is, load densities of 100, 500, and 1,000 kva per mile, conductor sizes of 2/0 and 4/0, etc., but (similar to figures 10 and 11) the additional benefits are plotted as dollars benefit per kilowatt of feeder capacity rather than per feeder

Additional benefits include:

1. Released feeder capacity
2. Released distribution-transformer capacity

**Figure 13**

These curves cover the same set of conditions as curves of figure 8 except that the additional benefit of increased revenue has been added. In this case the additional benefits have been plotted in dollars per feeder. It should be noted in comparing these data with those of figure 8 that the item of additional revenue still leaves the application of secondary capacitors somewhat doubtful except at light load densities. It may be noted, however, that for a ratio of transformer kilovolt-amperes to feeder demand of two, the secondary capacitors appear to somewhat of an advantage at all three of the load densities considered



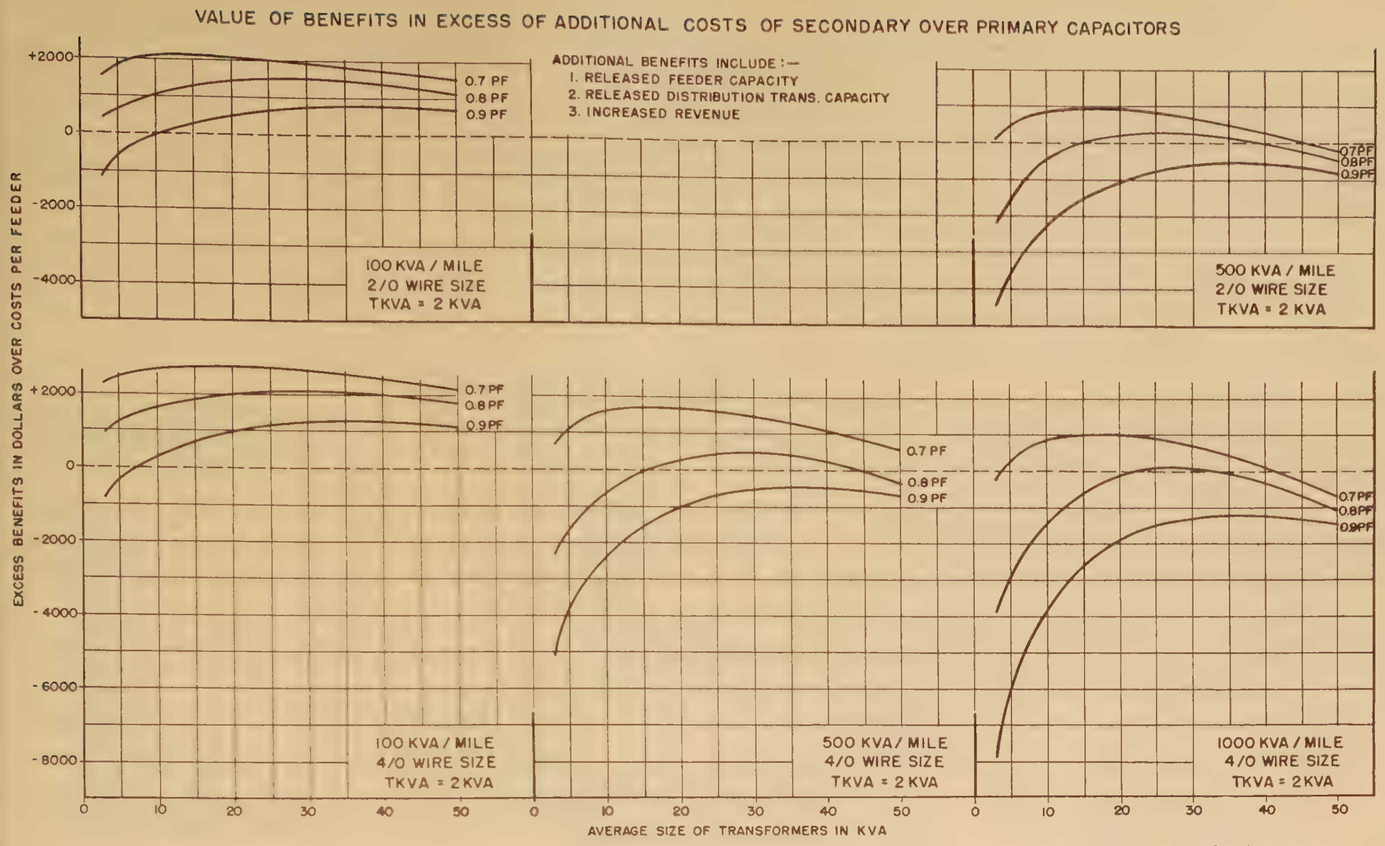
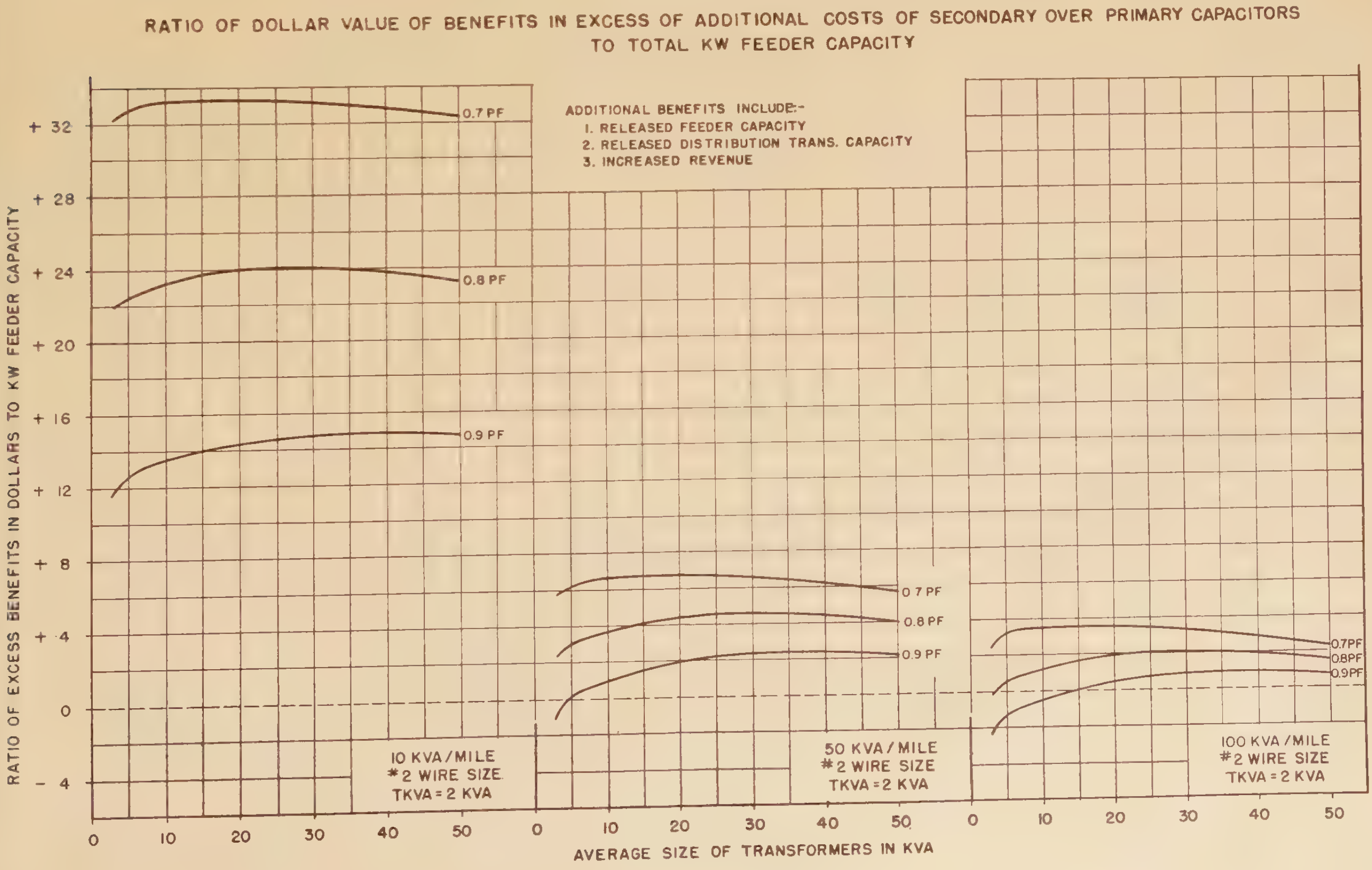


**Figure 14 (above)**

The data plotted here are entirely similar to those of figure 9 and cover a similar set of conditions, but include the additional benefit of increased revenue. The additional benefits of primary over secondary capacitors have been plotted in this case as dollars benefit per feeder. Here again it will be noted that the item of additional revenue does not greatly change the over-all picture as shown in figure 9. Secondary capacitors here appear to be attractive only at the load density of 100 kva per mile, except at low power factors

**Figure 15 (below)**

The data plotted here cover a similar set of conditions as those plotted in figure 10, except the additional item of increased revenue has been included in the benefits. As in figure 10 the value of additional benefit of primary over secondary capacitors has been plotted as total dollars benefit per kilowatt of feeder capacity, rather than per feeder



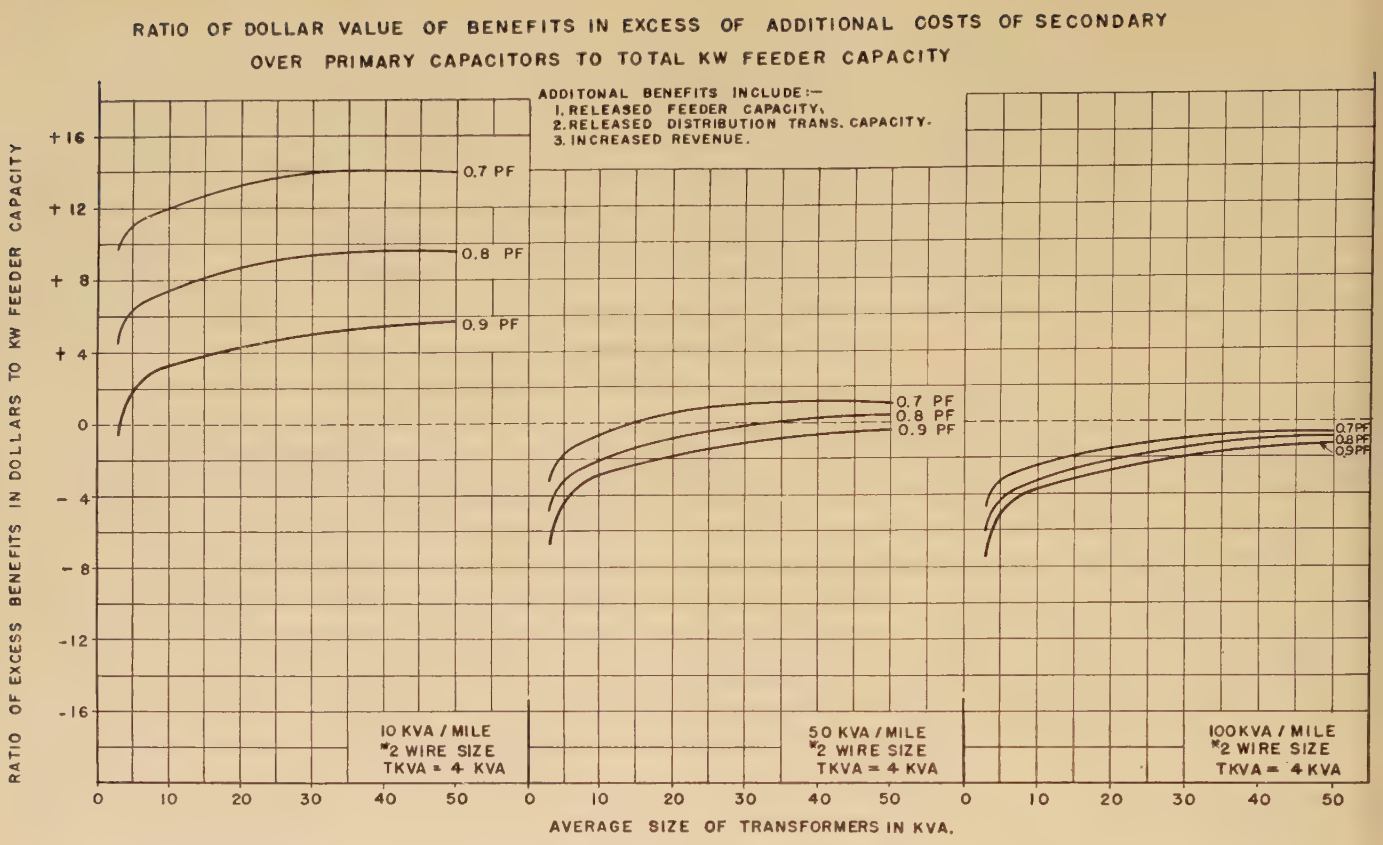
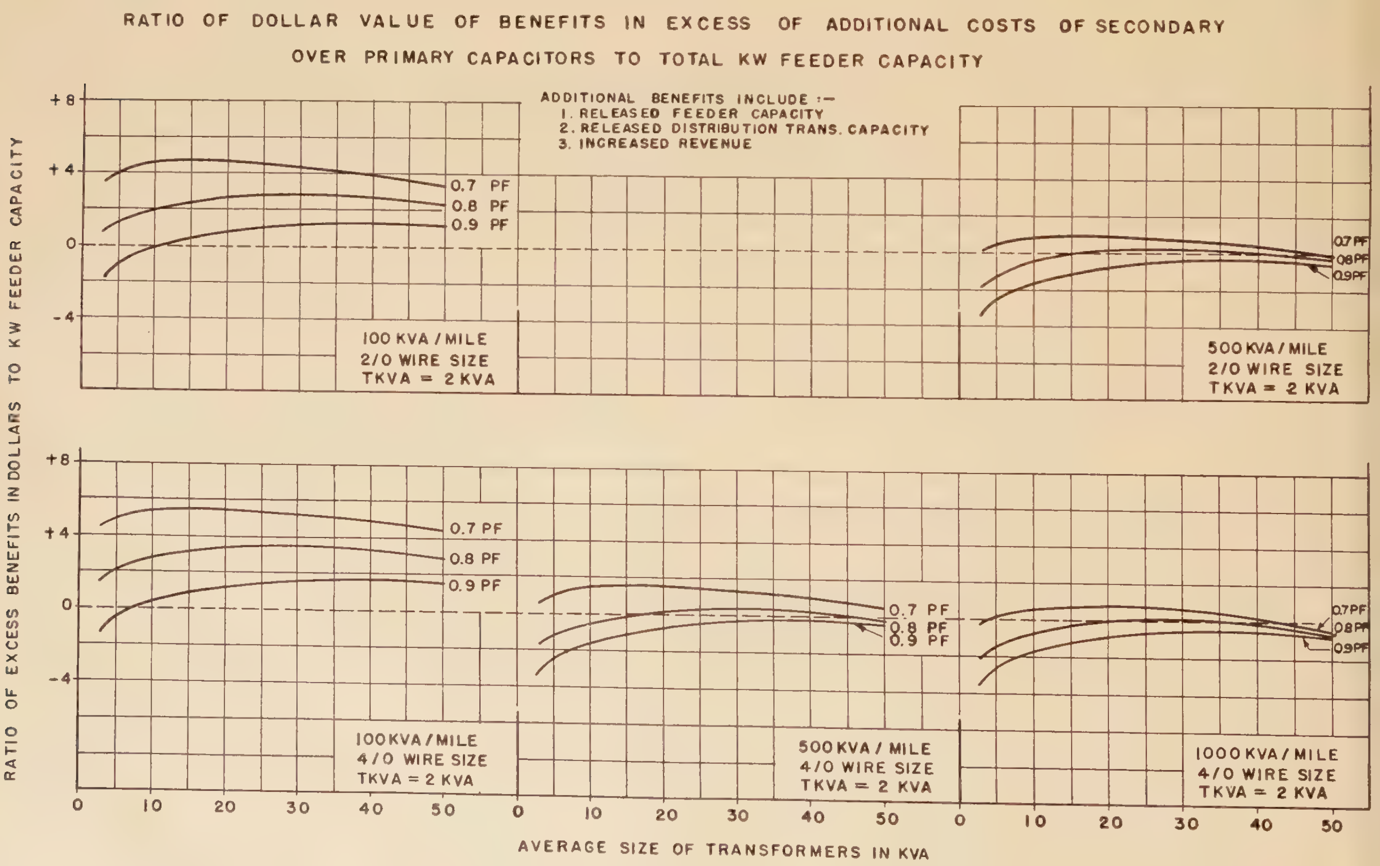


**Figure 16 (above)**

The data plotted here cover the same set of conditions as figure 11 except that the item of additional revenue has been included as a benefit. As in figure 11, the value of additional benefit of primary over secondary capacitors has been plotted as total dollars benefit per kilowatt of feeder capacity, rather than per feeder

**Figure 17**

The data plotted here cover the same set of conditions as considered in figure 12 except that the item of additional revenue has been included as an additional benefit. The value of additional benefit of primary over secondary capacitors has been plotted as total dollars benefit per kilowatt of feeder capacity, rather than per feeder



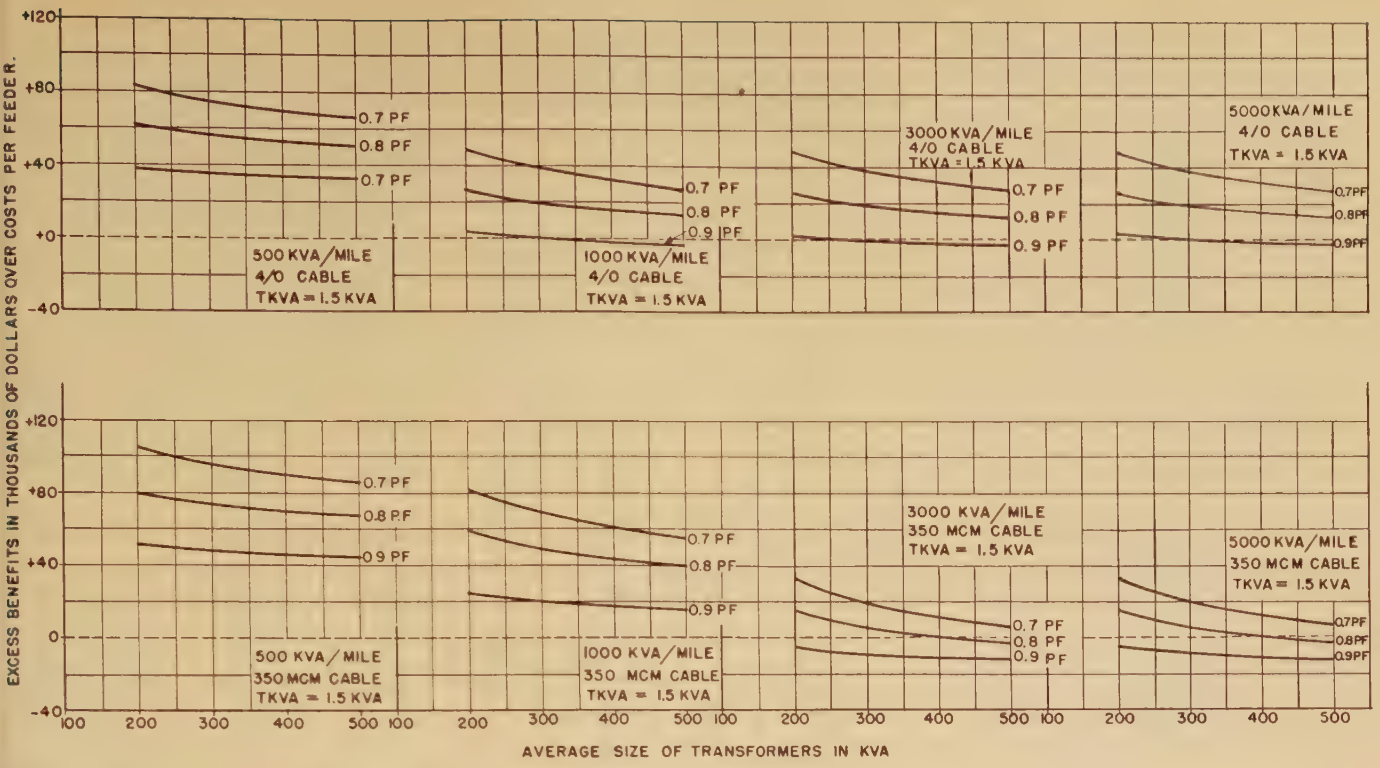


**Figure 18 (above). Value of benefits in excess of additional costs of secondary over primary capacitors for secondary network**

Figures 8 to 17 have summarized the results of a comparative analysis of primary over secondary capacitors on overhead lines covering a wide range of conditions. The data plotted here are similar to the foregoing but cover the secondary network application. Total additional benefits include (1) released feeder capacity, (2) released distribution transformer capacity, and have been plotted in dollars per feeder. Load densities were assumed to be 500, 1,000, and 3,000 and 5,000 kva per mile. The primary 13-kv cable was assumed to be alternatively 4/0 and 350,000 circular mil. Ratio of transformer kilovolt-amperes to diversified demand was assumed to be 1.5

Average size of distribution transformers ranged from 200 to 500 kva. It may be noted that, except at a load density of 500 kva per mile the secondary capacitor appears to be at somewhat of an advantage over the primary capacitor

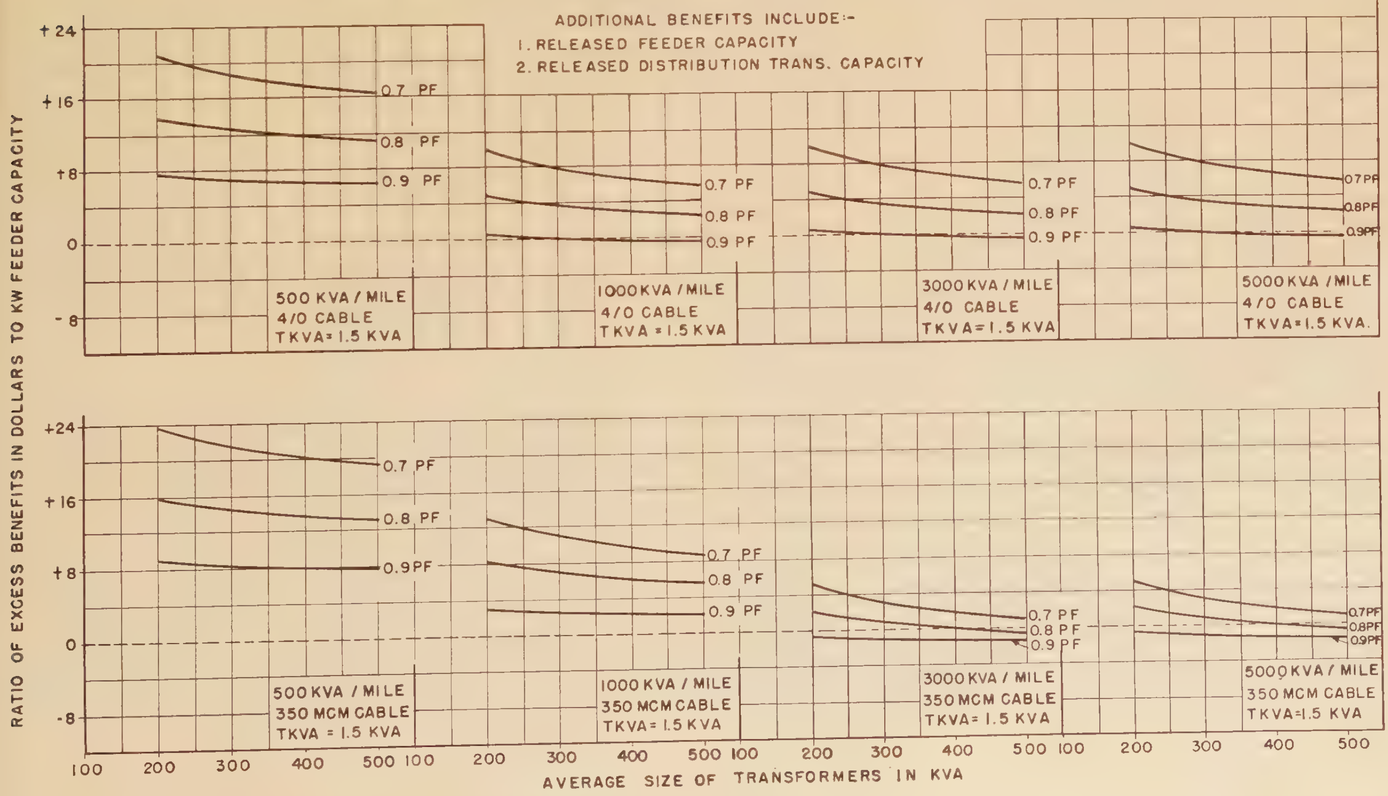
Additional benefits include:

1. Released feeder capacity
2. Released distribution-transformer capacity

**Figure 19**

The set of data considered here is the same as that considered in figure 18 except that the value of additional benefit of secondary over primary capacitors has been plotted as dollars benefit per kilowatt of feeder capacity rather than dollars benefit per feeder

RATIO OF DOLLAR VALUE OF BENEFITS IN EXCESS OF ADDITIONAL COSTS OF SECONDARY OVER PRIMARY CAPACITORS FOR SECONDARY NETWORKS TO TOTAL KW FEEDER CAPACITY



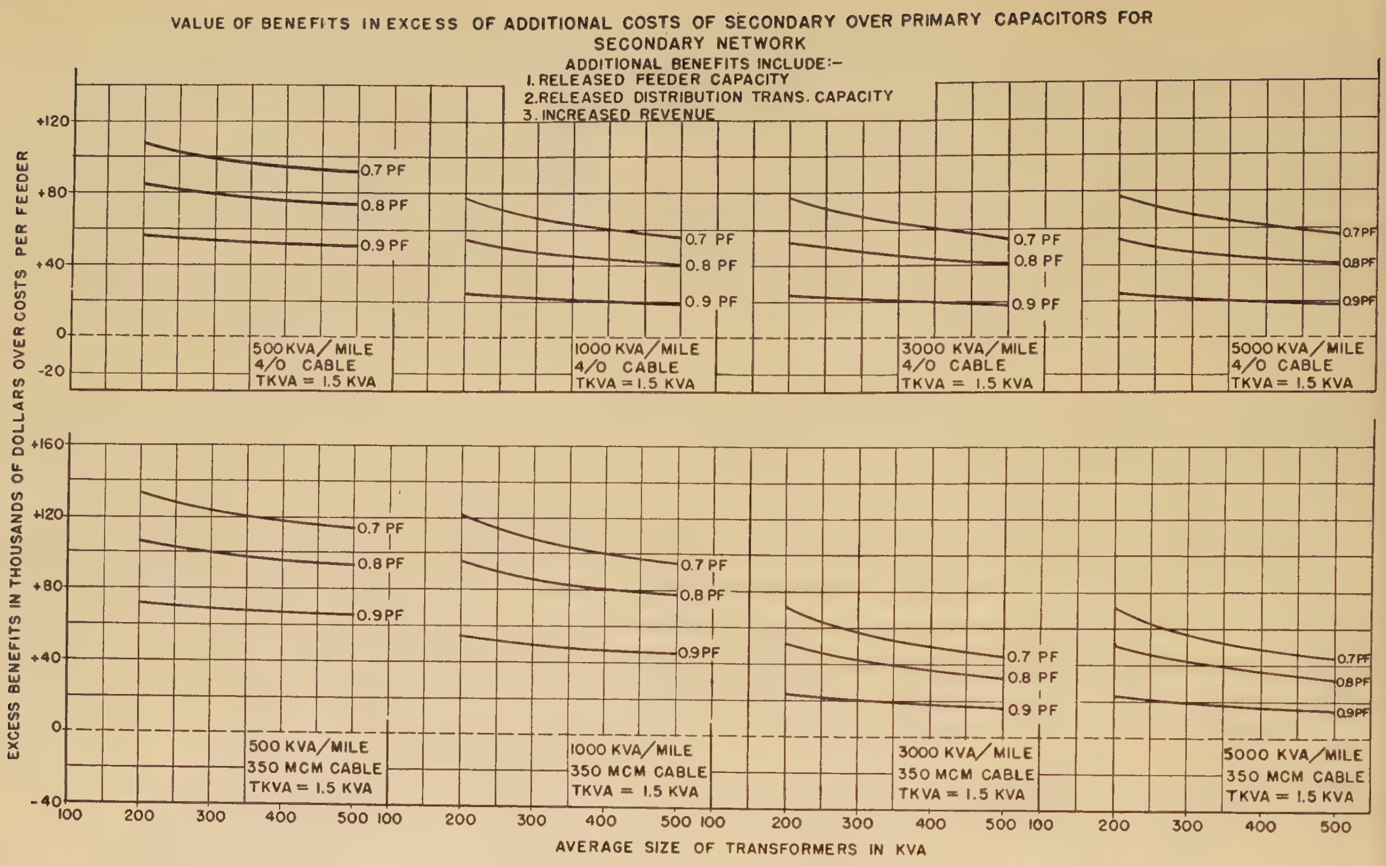


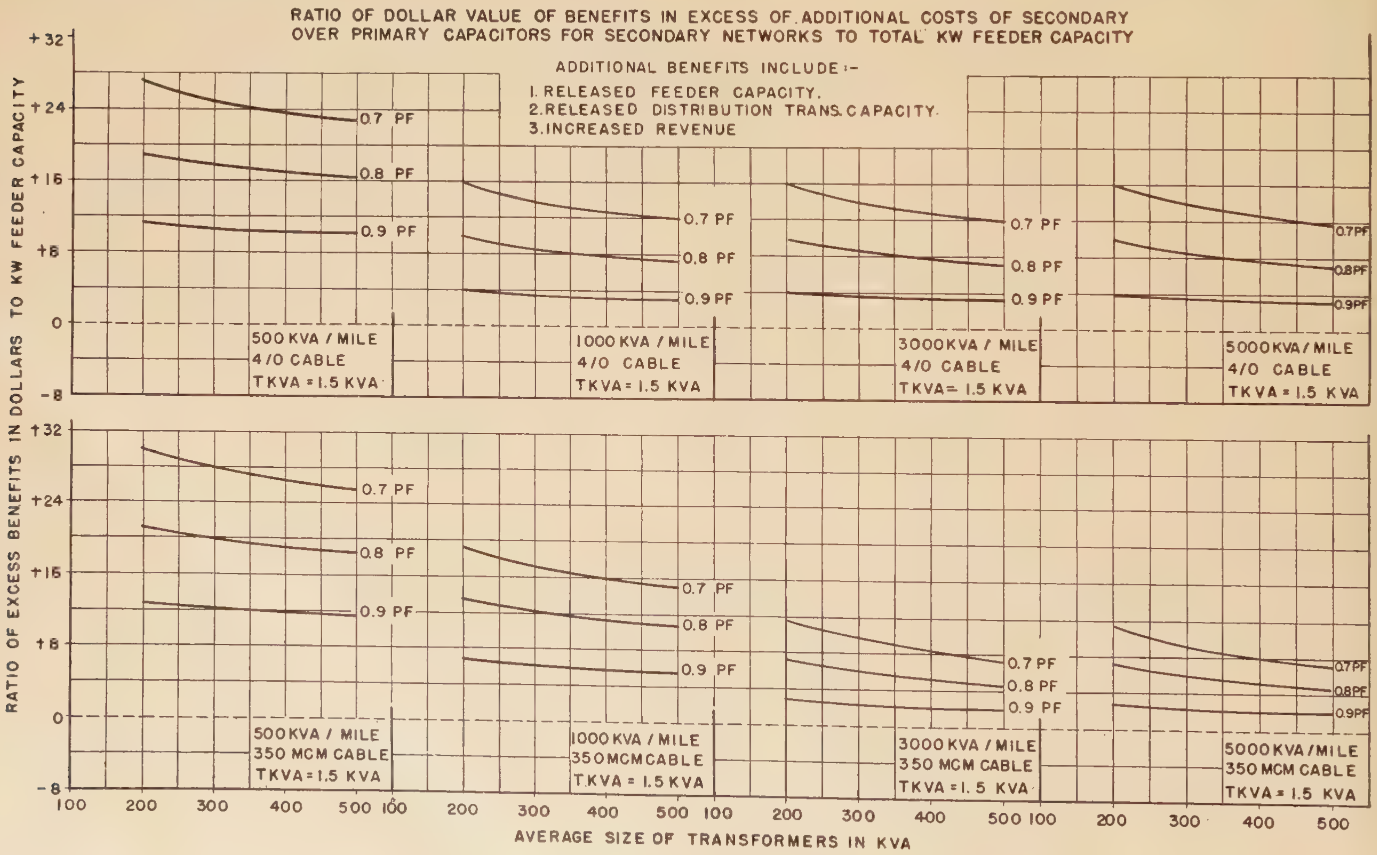
**Figure 20 (above)**

This set of curves is similar to those of figure 18 except that the item of increased revenue has been included as a benefit. Here the value of additional benefits of secondary over primary capacitors has been plotted in total dollars benefit per feeder

It may be noted that the item of increased revenue increases the total benefit to such an extent that the secondary capacitors appear to be of a considerable advantage in all cases considered over the primary capacitors

**Figure 21 (below)**

The data plotted here are similar to that of figure 20 except that the item of increased revenue has been included as a benefit. Similar to figure 20 the data here have been plotted as total dollars benefit per kilowatt of feeder capacity



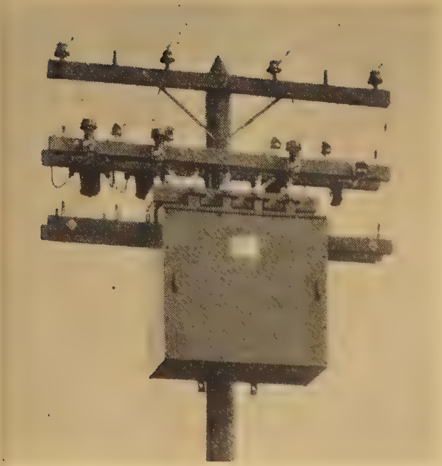


Figure 22

This illustration shows a 180-kva primary line capacitor for urban type of feeders. This type of equipment consists of a number of indoor capacitor units mounted inside a ventilated weatherproof housing

was assumed to be ten per cent and on the 13.8-kv underground secondary network feeders five per cent except where the thermal capacity of the cable would be exceeded. With this criteria for line capacity and the range of load densities used, the overhead lines varied in length from 2.2 miles to 17.8 miles while the underground network feeders varied in length from 3.5 miles to 12.7 miles. Similarly kilovolt-ampere peak loads varied from 173 kva to 2,520 kva on the overhead lines and from 3,500 to 9,000 kva on the network feeders.

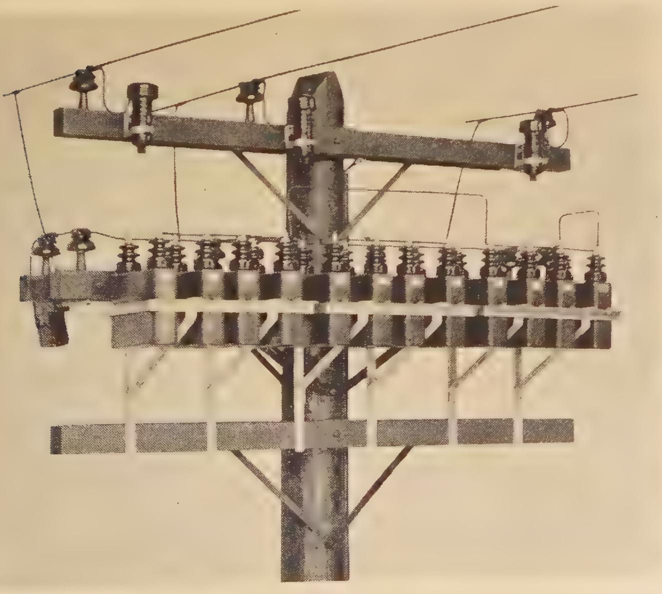


Figure 23

Here is shown another 180-kva primary-line capacitor bank made up of a number of individual outdoor units. This type of installation is functionally identical with that shown in figure 22 but is frequently preferred because it has a somewhat lower installed cost

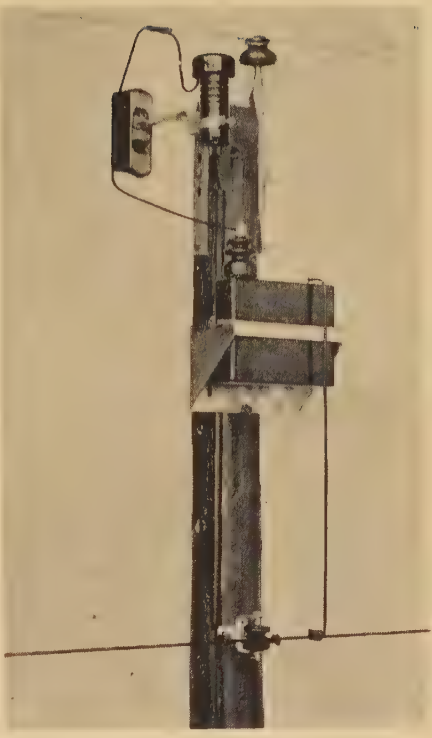


Figure 24

This is a typical installation of a 15-kva primary-line capacitor for single-phase rural service

For each case considered, additional kilowatt line capacity, released transformer capacity, and increased revenue were evaluated in dollars per line and dollars per kilowatt of line capacity. The methods used for these evaluations are tabulated in the appendix.

Figure 3 gives the capacitor installed costs used in making this study. These were approximately selling price plus 20 per cent for installation. On this basis 4-kv capacitors have an installed cost of $7.55 per kilovolt-ampere and 13-kv capacitors have an installed cost of $12.60. The secondary units have a variable cost per kilovolt-ampere, since the unit cost varies with size, but on the secondary network application the cost is fixed at $22.40 per kilovolt-ampere, since all banks of 208-volt capacitors are in increments of 5-kva units.

The value of transformer capacity also varies with size of installation. The values used in this study for the radial overhead line and underground network transformer costs are summarized in figure 4 and figure 6, respectively.

The unit line costs used are:

Three-phase number 2 4-kv overhead—$2,763 per mile
Three-phase number 2/0 4-kv overhead—$3,540 per mile
Three-phase number 4/0 4-kv overhead—$4,450 per mile
Three-phase number 4/0 13.8-kv cable—$17,400 per duct mile
Three-phase 350,000-circular-mil 13.8-kv cable—$20,100 per duct mile

These values are based upon averages of actual installed costs. Their absolute values may be in error for specific localities but their comparative values are accurate. These line costs were used to determine the value of a kilowatt of line capacity in each case.

## Examination of Results

In order to obtain any reasonable appraisal of the merits of the secondary capacitor on the distribution system, it was necessary to analyze a fairly wide range of circuit and load conditions. To present adequately the results a rather

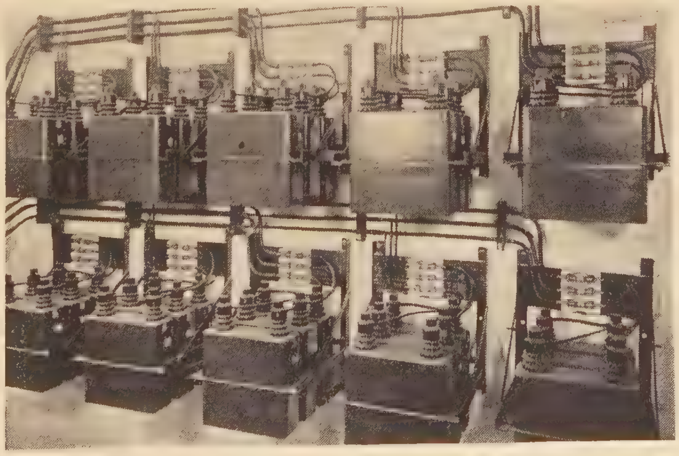
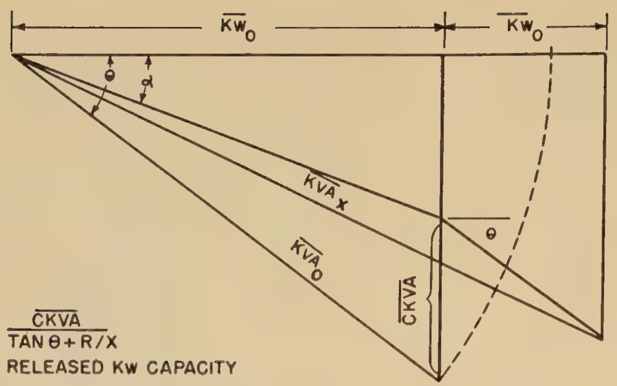


Figure 25

This illustration shows a 150-kva three-phase bank of 208-volt capacitors installed in a building vault for reactive kilovolt-ampere correction on a secondary network



$\overline{Kw_O} = \frac{\overline{CKVA}}{TAN\ \theta + R/X}$

$\overline{Kw_O}$ = RELEASED Kw CAPACITY

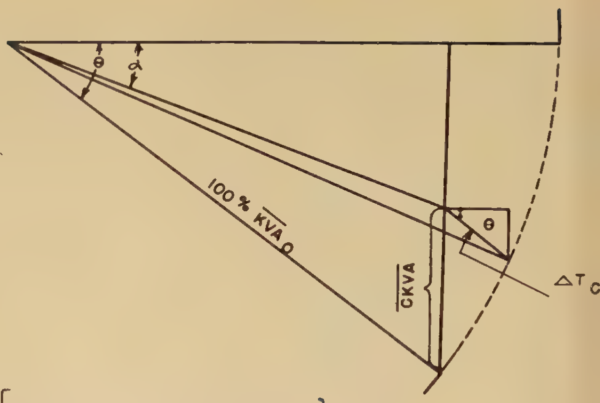
$\overline{CKVA}$ = CAPACITOR CORRECTION

R = LINE RESISTANCE

X = LINE RESISTANCE

**Figure 26**

The above diagram shows the vector relations existing between the pertinent quantities when capacitors are used to release feeder capacity where voltage drop is the limiting factor. For any particular capacitor having a **kva** rating of **Ckva** the above relation for $\Delta kw_0$ is the additional key which can be carried on the line without exceeding the voltage drop on the feeder existing before the capacitors were applied. In the above relation values of **kva**, **kw**, or **Ckva** may be expressed either as such or as percentages



$$\overline{\Delta T_C} = \left[\left(\frac{\overline{CKVA}}{\overline{KVA_O}} \sin\theta - 1\right) + \sqrt{1 - \frac{\overline{CKVA}}{\overline{KVA_O}}^{2} \cos^{2} O}\,\right] \overline{KVA_O}$$

$\overline{\Delta T_C}$ = RELEASED KVA CAPACITY

$\overline{CKVA}$ = CAPACITOR KVA CORRECTION

KVA = NOMINAL KVA RATING

**Figure 27**

The above diagram shows the vector relations existing between the pertinent quantities when capacitors are used to release capacity when kilovolt-ampere demand is the limiting factor. For any capacitor correction having a rating of **Ckva**, the above relation for $\Delta T_c$ is the additional kilovolt-ampere which can be carried at the initial load power factor without exceeding the nominal 100 per cent **kva**. In the above relation the values of **kva**, or **Ckva** may be expressed either as such or as percentages

large number of curves were necessary since five variables were involved—that is, power factor, load density, conductor size, diversity, and average transformer size. Moreover, it seemed necessary to prepare the results both considering and not considering increased revenue as a benefit since this item is controversial.

To show clearly when the secondary capacitor is to be preferred, it is necessary only to plot the difference in dollars between the capital value of the additional benefits which secondary capacitors have over primary capacitors and the capital value of the additional costs of secondary over primary capacitors. If the additional benefits exceed the additional costs, the secondary capacitor is a sound investment.

In figures 8 to 21, therefore, this difference between additional benefits and additional costs has been plotted as a function of the various circuit and load conditions. It has been plotted, first in dollars per feeder, and second, in dollars per kilowatt of feeder capacity. It seemed advisable to present the picture both ways since the feeders varied considerably in length and loading, they being alike only in maximum allowable voltage drop.

In examining figures 8 to 21, note that the dollar benefits or deficiency consist of the sum of the following items:

1. Capital value of additional distribution transformer capacity.

2. Capital value of additional feeder capacity.

3. Capital value of additional revenue (capitalized on the basis of 12.5 per cent annual carrying charge).

As stated above, the data were also calculated omitting the third item of revenue. Figures 8 to 17 cover the overhead lines studied, and figures 18 to 21 cover underground secondary networks. Figures 13, 14, 15, 16, 17, 20, and 21 include the item of additional revenue as a benefit and the others omit it.

Consider the comparative effect of the several variables individually. First consider the network versus the overhead line. With a few minor exceptions all networks favor the secondary capacitor whether the item of revenue is allowed or not. With many of the overhead lines, on the other hand, the secondary capacitor cannot be justified. The reasons for this are more or less evident. The value of released transformer capacity in a secondary network, in most cases, is worth considerably more than transformer capacity on poles. Also underground primary feeder capacity is worth considerably more per kilowatt than overhead lines in many cases. Accentuating these effects there are also the contributing factors that 13.8-kv capacitors cost substantially more than do 4-kv units. Also the lowest cost of all secondary capacitors is the five-kva unit used on the secondary network (see figure 3).

In virtually all cases the lower power factors favor the secondary capacitor to a much greater extent than do the higher power factors. This is particularly true at light load densities and with the smaller conductor sizes.

The effect of load density is especially interesting. On the overhead lines, it is only at the very light load densities that secondary capacitors can be justified, in many cases even though additional revenue is allowed. In the case of the network, while secondary unit nearly always is justified, the maximum benefits likewise occur at the lighter load densities.

The influence of transformer size varies. On overhead lines, in many cases the additional benefits increase with size of transformer, while in other cases there is an optimum size varying from 10 to 30 kva. With the networks the value of additional benefits decrease with transformer size.

Large conductors appear to offer less benefits than do small conductors on radial feeders, but on the network feeders the reverse is true. As would be expected, the greater the ratio of transformer kilovolt-amperes to diversified peak kilovolt-ampere demand, the less attractive are secondary capacitors.

## Conclusions

While the results of this study, as in all economic studies of this type, have greater comparative value than absolute value when applying to specific systems, they do establish the following general conclusions:

1. On underground secondary networks,

particularly those served from primary voltages of 11-kv or greater, the secondary capacitor appears to have an important field of application.

2. On conventional overhead systems, particularly those having primary voltages of 6,900 volts or less, the secondary capacitor has a very limited field of application. It is doubtful if secondary capacitors can be proved in on any overhead line except in cases of rather low power factor. However, on overhead systems incorporating banked secondaries, since many of the inherent advantages of secondary capacitors on low-voltage networks are duplicated, the secondary capacitor in many cases may easily be proved in.

3. Low power factors establish conditions on any distribution system—network or radial—which strongly favor secondary capacitors.

4. Secondary capacitors must be applied with considerable care—much more so than primary capacitors—if the hypothetical calculated benefits are to be realized. Accurate setting of the contact-making voltmeter and the compensator together with proper location and size of the secondary units are very essential to obtain the calculated additional benefits.

5. If economic analysis shows that a secondary capacitor adjacent to a distribution transformer cannot be justified, only a cursory analysis is necessary to show that, under the same circuit and load conditions, a large number of smaller units adjacent to meter boxes likewise cannot be justified. This is owing to the rapid increase in cost per kilovolt-ampere as the size of the unit comes down (see figure 3). It is somewhat doubtful under any circuit or load conditions if a plan incorporating a number of small units located at meter boxes could ever be justified.

# Appendix

## Releasing System Capacity With Capacitors Where Voltage Drop Is the Limiting Factor

The kilowatt carrying capacity of any part of a system, such as a distribution feeder, where the limitation on capacity is voltage drop, is:

$$\boldsymbol{kw}_0 = \frac{10\ \boldsymbol{kv}^2\ v}{R + X \tan\theta} \qquad (1)$$

$v$ = allowable per cent volts drop
$R$ = total resistance in ohms
$X$ = total reactance in ohms
$\theta$ = uncorrected power factor angle
$\boldsymbol{kv}$ = line kilovolts
$\boldsymbol{kw}_0$ = kilowatt capacity

If the allowable drop $v$ is increased by an amount $\Delta_v$ per cent for one reason or another, the increase in kilowatt capacity is

$$\Delta\boldsymbol{kw}_0 = \frac{10\ \boldsymbol{kv}^2\ \Delta\boldsymbol{v}}{R + X \tan\theta} \text{(refer to figure 26)} \qquad (2)$$

If a primary capacitor is applied at the end of the line (or at a distance corresponding to $R$ and $X$), the per cent voltage rise due to the capacitor is

$$\Delta\boldsymbol{v} = \frac{\boldsymbol{Ckva}\ X}{10\ \boldsymbol{kv}^2} \qquad (3)$$

$\boldsymbol{Ckva}$ = kilovolt-amperes of capacitor

and the resultant kilowatt capacity of the line is:

$$\boldsymbol{kw}_x = \frac{10\ \boldsymbol{kv}^2\ (v + \Delta v)}{X \tan\theta_0 + R} \qquad (4)$$

$$= \frac{10\ \boldsymbol{kv}^2\ v + X\ \boldsymbol{Ckva}}{X \tan\theta_0 + R}$$

A specified amount of primary capacitor correction gives a definite voltage rise on the feeder. If this same kilovolt-amperes of primary correction is applied to the secondary side of the distribution transformers and if it is uniformly distributed in proportion to the distribution transformer capacity, there will be an additional per cent voltage rise due to the transformer reactance of

$$\Delta\boldsymbol{v}_t = X_t \frac{\boldsymbol{Ckva}}{\boldsymbol{Tkva}} \qquad (5)$$

$X_t$ = transformer reactance in per cent
$\boldsymbol{Ckva}$ = total capacitor correction in kilovolt-amperes
$\boldsymbol{Tkva}$ = total installed transformer kilovolt-amperes

This additional voltage rise is not effective in increasing the line kilowatt capacity, however, unless it is confined to that portion of the feeder beyond the transformer location at which the feeder voltage drop is equal to the voltage rise in the transformer effected by the capacitor. If this method of applying the secondary unit is adopted, the additional voltage rise will be:

$$\Delta\boldsymbol{v}_t = X_t \frac{\boldsymbol{Ckva}}{(\boldsymbol{Tkva})K} \qquad (6)$$

where $K$ is defined by the relation

$$K^3 - K + \frac{(\boldsymbol{Ckva})}{(\boldsymbol{Tkva})} \frac{X_t}{10} = 0 \qquad (7)$$

The additional increase in primary line kilowatt capacity accruing from secondary over primary capacitors is therefore:

$$\Delta\boldsymbol{kw}_t = \frac{20\ \boldsymbol{kv}^2\ \boldsymbol{Ckva}\ X_t}{\boldsymbol{Tkva}\ K(\tan\theta + R/X)X} \qquad (8)$$

If the peak diversified demand on the feeder is $\boldsymbol{Kva}_0$ before correction, then

$$\boldsymbol{Tkva} = n\ \boldsymbol{Kva}_0 \qquad (9$$

where $n$ is the ratio of installed transformer capacity to diversified demand. Also:

$$\boldsymbol{Ckva} = \boldsymbol{Rkva} \qquad (10)$$

where $\boldsymbol{Rkva}$ is the average reactive kilovolt-amperes on the feeder during a 24-hour period.

Figures 5 and 7 are plots of equation 5 for transformers on overhead lines and secondary networks, respectively. These curves show the voltage rise effected by capacitors for various amounts of capacitor correction. It is assumed in each case that the feeder power factor has been corrected to unity and that $n$ = 2, a fairly representative value for most distribution feeders. It may be noted that the maximum voltage rise is about one per cent for transformers on overhead lines and about two per cent for transformers in secondary networks.

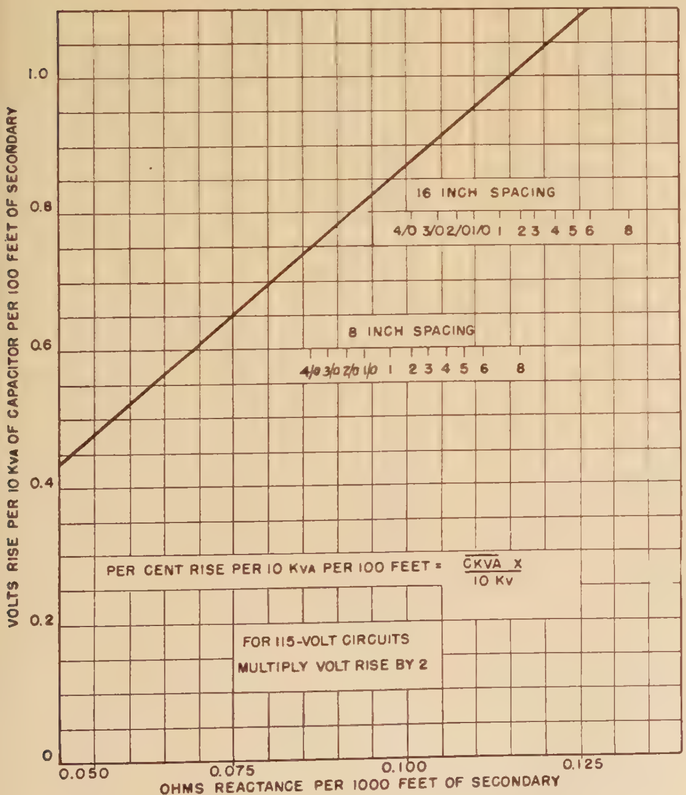


FIGURE 28. VOLTAGE RISE ON 230-VOLT, 3-WIRE, 1-PHASE, SECONDARIES PER 10 KVA OF 230-VOLT CAPACITOR

**Figure 28**

This curve shows the voltage rise on 230-volt three-wire single-phase secondaries per ten kva of 230-volt capacitor. For 115-volt secondaries the voltage rise should be multiplied by two

### Releasing System Capacity With Capacitors Where Temperature Rise Is the Limiting Factor

The capacity of generators, transformers, etc., is usually limited by temperature rise, that is, kilovolt-ampere demand, rather than by voltage drop. Figures 26 and 27 illustrate the difference in these two limiting factors vectorially. In figure 26, $\Delta \boldsymbol{kw}_0$ is the additional kilowatts that can be carried after adding capacitor correction $\boldsymbol{Ckva}$, with exactly the same voltage drop as obtained before correction. $\Delta \boldsymbol{kw}_0$ is always assumed to be added at the uncorrected power factor angle, $\theta$. In figure 27 $\Delta \boldsymbol{kva}$ is the additional kilovolt-amperes at power factor $\theta$ which can be added after correction without the net resultant kilovolt-amperes exceeding the initial.

In general, for a given amount of capacitor correction, the released capacity, where voltage drop is the limiting factor, usually substantially exceeds that where kilovolt-ampere demand is the limiting factor.

In figure 26,

$$\Delta \boldsymbol{kw}_0 = \frac{\boldsymbol{Ckva}}{\tan\theta + R/X} \tag{11}$$

The values $R$ and $X$ are resistance and reactance from the substation to any particular capacitor installation having a value $\boldsymbol{Ckva}$ and $\Delta \boldsymbol{kw}_0$ is the released capacity for that particular installation: or $R$ and $X$ may be considered the resistance and reactance to the load center if $\boldsymbol{Ckva}$ equals the total capacitor correction. In equation 11, $\Delta \boldsymbol{kw}_0$ and $\boldsymbol{Ckva}$ may be expressed either as kilowatts and kilovolt-amperes or as per cent.

In figure 27,

$$\Delta \boldsymbol{Kva} = \left[\left(\frac{(\boldsymbol{Ckva})}{(\boldsymbol{Tkva})K}\sin\theta - 1\right) + \sqrt{1 - \frac{(\boldsymbol{Ckva})^2}{(\boldsymbol{Tkva})^2K}\cos^2\theta}\,\right]\boldsymbol{Tkva}\,K \tag{12}$$

$\boldsymbol{Ckva}$ = capacitor correction
$\boldsymbol{Kva}$ = released kilovolt-ampere capacity
$\boldsymbol{Tkva}$ = transformer kilovolt-ampere capacity
$\theta$ = uncorrected power-factor angle

On a percentage basis equation 12 becomes

$$\Delta T_c = (C\sin\theta - 100) + \sqrt{100^2 - C^2\cos^2\theta} \tag{13}$$

$\Delta T_c$ = per cent released capacity
$C$ = per cent capacitor correction
$\theta$ = uncorrected power-factor angle

In equation 12, $\Delta T_c$ and $C$ are percentages of the kilovolt-ampere capacity of the transformer receiving correction. Equation 13 obviously applies to any size of transformer, substation, etc.

The value $\Delta T_c$ may also be calculated as a function of power-factor angles before and after correction:

$$\Delta T_c = -100\cos\theta[\cos\theta + \sin\theta\tan\alpha] + 100\cos^2\theta\sqrt{1 + 2\tan\theta\tan\alpha - \tan^2\alpha + \frac{\tan^2\theta}{\cos^2\theta}} \tag{14}$$

$\theta$ = power-factor angle before correction
$\alpha$ = power-factor angle after correction

### INCREASE IN REVENUE

The increase in kilowatt-hour output effected by the voltage rise as calculated in equation 6 is usually assumed to increase as the 1.6 power of increase in average voltage level over a 24-hour period. On this basis the additional kilowatt-hours due to secondary capacitors as compared with primary capacitors will be

$$\Delta \boldsymbol{kw\text{-}hr} = \left[\left(\frac{\dfrac{(\boldsymbol{Ckva})}{(\boldsymbol{Tkva})K}\dfrac{X_t}{2} + 100}{100}\right)^{1.6} - 1\right] \times \boldsymbol{kw}_0 \times \text{L.F.} \times 8{,}760 \tag{15}$$

$\boldsymbol{kw}_0$ = peak feeder kilowatts
L.F. = load factor

This additional kilowatt-hour output is usually evaluated at \$0.02 per kilowatt-hour and capitalized at 12.5 per cent per annum.

## Discussion

**J. D. Stacy** (General Electric Company, Pittsfield, Mass.): Mr. Starr's excellent paper re-emphasizes the extensive application for capacitors on central station systems. It is interesting to note that a large number of utilities throughout the country have applied capacitors with considerable savings—

1. Because of improvement of voltage conditions which has deferred installation of new feeders, feeder positions, cable, etc.
2. Because of release of substation capacity.
3. Due to reduced losses.

This extensive application has been the result of several important factors:

First, the improvements in capacitor design and reliability which have been effected during the last 10–12 years.

Secondly, the simultaneous marked reductions in installed cost of capacitors during the same period.

Capacitor design improvements have covered not only improvements in paper, foil, and the other solid materials used, but principally the substitution of chlorinated diphenyl for the oil previously used. The new liquid has:

(*a*) Reduced the size and weight of capacitors because of its considerably higher dielectric constant compared with that of oil.

(*b*) Increased the dielectric strength not only because of its own higher dielectric strength, but because of the improved distribution of voltage stress through the dielectric resulting from the fact that the dielectric constant of liquid and cellulose are practically the same.

In addition, careful attention to the process of vacuum drying and impregnation has been a considerable factor in bringing quality to its present high level.

As a consequence of these factors and the standardization of ratings, capacitor installed costs have been reduced sharply during the last ten years. The average cost per kilovolt-ampere of capacitors of all voltages is now approximately 36 per cent of that in effect in 1929—a reduction of 64 per cent.

**L. M. Olmsted** (Duquesne Light Company, Pittsburgh, Pa.): Mr. Starr's paper very ably indicates the field in which secondary shunt capacitors are more attractive economically than primary capacitors. In order to secure the utmost advantage for the secondary capacitors, he has assumed that the capacitors will be used only on transformers far enough from the feeding point that the rise in voltage caused by the capacitive current will not raise the secondary voltage above that of the transformers at the feeding point. In this way he makes effective the additional voltage correction through the reactance of the more remote transformers to offset primary-circuit voltage drop, thereby increasing the load-carrying ability of the primary circuit beyond that possible with the same capacity in primary capacitors.

While such a practice is workable, it would require continual supervision to keep it in proper relationship to the system changes which invariably accompany circuit extensions and load growth. This additional supervision would be a disadvantage, tending to reduce possible economies, particularly on the usual overhead radial system, with numerous small transformers. Underground systems, having larger transformers, generally receive more careful supervision and probably would have the capacitors relocated as required. It is fortunate, therefore, that the field of economic application for secondary capacitors is limited mostly to underground systems.

**F. M. Starr:** I agree with Mr. Olmsted that the method described in this paper for obtaining some additional feeder kilowatt carrying capacity by means of secondary capacitors, necessitates very careful application engineering, and would require continual supervision and checking. This is one of the intangibles which would tend to discourage the use of secondary capacitors if economic advantage were on the border line.

In closing, I should like to emphasize one further point: In the paper 220-volt capacitors were compared with 4,000-volt capacitors, and 208-volt capacitors were compared with 13,000-volt units. In specific cases it might be desirable to compare, for example, 440-volt capacitors with 6,900-volt units. There are several other comparisons which it might be desirable to make in specific cases. It is well to note, therefore, that any general conclusions drawn here do not necessarily apply in some of these specific comparisons. It is further of interest to note in connection with these comparisons that any very substantial change in the price of capacitors, which might be brought about by some new development, would again change the economics and conclusions of this problem.

Transactions

apers and Discussions Comprising Pages 243–306 of the 1939 Volume

# Considerations in Applying Ratio Differential Relays for Bus Protection

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THE PROBLEM of bus differential protection is receiving increased tention by relay engineers because of ıe serious consequences of a bus fault. everal cases of bus faults have recently ccurred indicating that regardless of care sed in the design of structures, some unxpected failure or accident may cause a isastrous outage. In spite of the many nprovements that have been made in the rotection of transmission lines in recent ears, little attention has been given to the rotection of station busses. This has een due partly to the impression that ıey were not particularly subject to faults ıd partly to the feeling that the protecve relays would do more harm than good ırough incorrect tripping. Recent exeriences, however, indicate that a bus ult, though of infrequent occurrence, can ıuse much greater damage and a longer ıtage period than many transmission line ults. Also, high-grade performance has een obtained when a bus protective heme is properly installed with due conderation given to the many factors which ight lead to faulty operation. The purpose of this paper is to discuss some of the nportant factors to be considered in bus fferential protection and the operating ıaracteristics and results of a field test ı a new bus differential relay.

The differential relaying scheme for rotecting a station bus does not differ principle from that which has long een used for the protection of a generator transformer bank. That is, current ansformers are located in all connections to the bus and a summation of all the secondary currents is made (figure 1). Under load conditions or for an external fault the summation of all the currents should equal zero, and, therefore, no current should appear in the operating winding of any relay connected across that circuit. For an internal fault, assuming faithful current-transformer response, the total amount of the short-circuit current should appear in the operating winding of the protective relay.

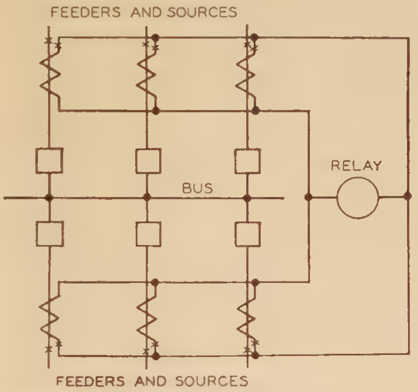

Figure 1. Differential protection for a six-circuit bus using an overcurrent differential relay

## Current-Transformer Performance

### A-C Saturation

In the case of a fault occurring external to the differential zone, the operating coil of the relay would receive no current whatsoever, if the performance of the current transformers was perfect. Actually, current often does appear in the operating coil of the relay upon the occurrence of external faults because of unfaithful transformer performance. Any one or more of the current transformers involved may be affected by a-c saturation because of insufficient iron in the current transformer core, an insufficient number of secondary turns, or excess burden in the secondary circuit for the magnitude of current involved. In general, the effect of a-c saturation has not been found to be particularly bad for differential relay protection.

### D-C Saturation

A second and more important factor affecting current-transformer performance, which has not been fully appreciated, is that arising from the effect of the d-c component of asymmetrical faults. The introduction of faster operating differential relays has brought this problem to the front, since with the slower operating relays formerly used, the effects of the d-c transient were over before tripping could occur. The effect of the d-c component of an asymmetrical current wave is such as to aggravate the saturation of current transformers to a far greater degree than the corresponding a-c component. The effect of this d-c component on the current transformer is to magnetize the current transformer core with a unidirectional flux which thus gives rise to the term d-c saturation of current transformers. The degree of this effect depends upon the d-c time constant of the primary circuit, the resistance and inductance of the secondary circuit of the current transformer affected, the amount and magnetic characteristics of the core, the ratio of the current transformer, and the magnitude of the primary current. The degree of d-c saturation is greater for the longer d-c time constants. This makes the problem more difficult, particularly for the protection of generator busses, since the time constant for a large generator may be as great as 0.3 seconds. High-voltage busses will, in general, have a time constant less than 0.3, ranging in value from approximately 0.13 down to 0.05, or even less if the bus is located a considerable distance from the generating station.

### Matched Current Transformers

On first thought it would seem practical to insure adequate performance of current transformers for differential protection by making all of the current transformers alike. However, it is found that even with standard current transformers built to the same specifications, there still remains some difference in their perform-

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per number 39-31, recommended by the AIEE mmittee on protective devices, and presented at e AIEE winter convention, New York, N. Y., nuary 23–27, 1939. Manuscript submitted ovember 12, 1938; made available for preprinting ecember 29, 1938.

M. Smith is section engineer and W. K. Sonne-ann is design engineer with the Westinghouse ectric and Manufacturing Company, Newark, J.; G. B. Dodds is relay protection engineer with e Duquesne Light Company, Pittsburgh, Pa.

For all numbered references, see list at end of per.

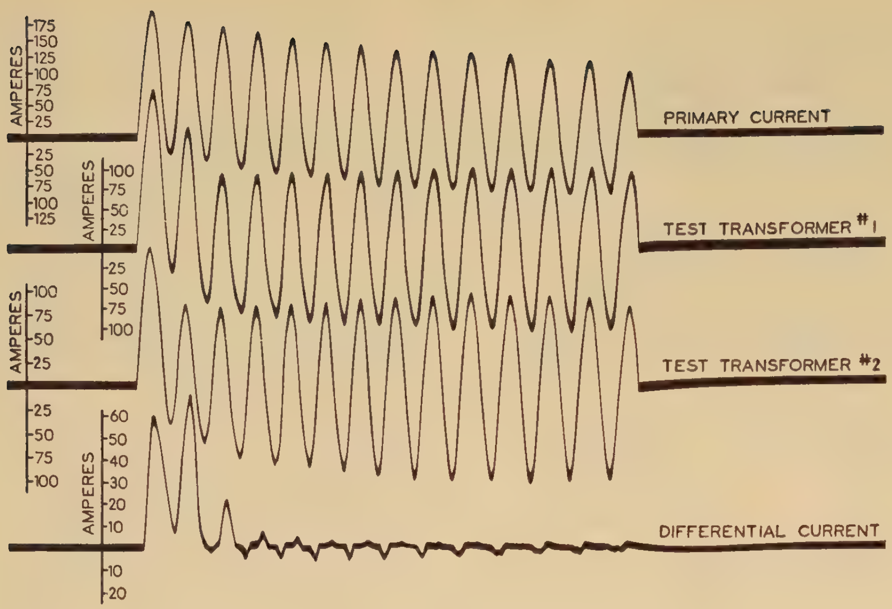


**Figure 2. Oscillogram showing effect of d-c saturation**

ance when subjected to asymmetrical short circuits. This is because their saturation curves will not match exactly at the high values of d-c excitation involved. Another reason why duplicate standard current transformers used throughout will not always give satisfactory performance is because the total short-circuit current may flow out to an external fault through one current transformer, but may be divided up among several current transformers in the leads to the bus from the various sources. For example, with a generator bus having two generators and two bus-tie breakers, an external fault of 60,000 amperes on a feeder may be divided up into 20,000 amperes feed-in through each bus-tie breaker and 10,000 amperes from each generator on the bus section. Obviously the current transformer in the outgoing feeder which must carry 60,000 amperes will be operating on a different portion of the saturation curve than the current transformers on the incoming leads. Therefore, unless the current transformer in the feeder circuit has been designed so that it will not saturate with an asymmetrical short circuit of 60,000 amperes, a difference or operating current is bound to occur for this type of fault in spite of any effort made to match the current transformer characteristics for symmetrical currents.

A more complete discussion of the effect of d-c transients on current transformer performance is available elsewhere.[1] However, no simple method has yet been made available which can be used to determine accurately the magnitude and duration of the difference in current transformer output for these conditions.

Figure 2 shows an actual test film in which two differentially-connected transformers were caused to saturate by d-c transient current. It may be noted that the outputs of the two test current transformers differ from each other, particularly through the first three positive peaks, and that during this time the difference current is a maximum. Also, neither secondary current records a true picture of the actual primary current. The correct value of the d-c component is obviously not reproduced. Measurements on the film also show that for the seventh cycle the a-c component for test current transformer number 2 was only 83 per cent of the true value.

### Blocking Resistors

One means of controlling the amount of difference current which may flow is by inserting a definite amount of fixed resistance in the difference or operating coil circuit. A well-accepted practice for improving the performance of differential protection has been the reduction and balancing of lead impedance in the secondary circuit and the increase of impedance in series with the differential relay. For example, many operating companies make a practice of running all current-transformer secondary leads in the differential circuit to a bus out in the switch yard, when only a single-element overcurrent relay is used, and then bringing to the relay only the necessary leads. This results in a minimum of secondary lead resistance to each current transformer secondary and does increase the burden in the differential circuit by the extent of the lead resistance to the relay. Several recent installations have extended this principle by the addition of a resistance in series with the operating winding of the differential relay in order to decrease the current through this path in case of an external short circuit. Recent tests have indicated that with ratio differential relays some discretion must be observed in the magnitude of resistance to be introduced in the differential circuit or failure to trip for an internal fault might result. This comes about from the fact that the secondary voltage of the current transformers required to force the differential current through the excess burden may reach a high value. As a result, the poorer current transformer may not be able to develop this voltage and is subjected to a reversal of current through its secondary. In other words, one current transformer may actually have its secondary current reversed so that a differential relay having restraint windings wound on the same magnetic circuit would not have the restraint torque canceled out, as should occur on an internal fault with this type of relay. Therefore, a failure to trip might easily occur, if the impedance in series with the operating winding is too high.

Figure 3 illustrates a test condition wherein too much impedance was used in the differential circuit for an internal fault condition. The polarity of connections was such that had both current transformers performed correctly, the loops of the current wave of current transformer number 1 would have dove-tailed with the primary current wave, while the wave for current transformer number 2 would have been exactly opposite in phase. For the first two cycles, current transformer number 1 reversed the current through current transformer number 2 without excessive wave-form distortion. At the end of two cycles, it will be noted that current transformer number 2 takes control of the circuit, reversing the current through current transformer number 1, accompanied by a severe distortion of wave form.

Without saturation, the output of the two test current transformers should have been 126 amperes each, as determined from their ratio and the magnitude of the primary current. The differential or operating coil current, then, should have been 252 amperes. An approximation of the actual currents flowing at the fifth cycle gives values of 61 amperes for current transformer number 1, 75 amperes for current transformer number 2, and 17 amperes for the difference current. This means that a 50 per cent ratio differential relay would not have operated for this test, since the ratio of the operating coil current to the smaller restraining coil current is only 28 per cent [(17/61) (100) = 28 per cent].

## Differential Relay Schemes

The fact that there are many successful bus differential relays in service at the present time, which are giving a relatively high degree of protection, does not indicate necessarily that difficulties will not be encountered on other systems or on these systems when future changes are made. It is also possible that on some of these installations an improper operation may yet occur because of the proper combination of circumstances. Otherwise, the satisfactory performance of existing installations has resulted from either a sufficiently high current setting or a long enough time to allow the transient to subside. Either of these factors tends to make a simple overcurrent relay satisfactory. There have been cases of false operation on a through fault involving d-c transient in which it is recognized that one or the other of these factors was not sufficiently high.

The magnitude of a phase-to-ground fault where a limited current exists often determines the setting of a differential relay. In such an application the use of a restrained or ratio differential relay would lessen the tendency for incorrect relay operation for heavy through faults. Of course, as pointed out elsewhere,[2] sufficient restraining windings must be provided so that on an external fault, short-circuit current must pass through at least one restraining winding. That is, current transformers must not be paralleled in such a manner that on a through fault on one of these circuits current would circulate between the secondaries of the two paralleled current tranformers. Under this condition only the difference in the outputs of the two current transformers would flow through a restraining winding and the operating winding in series, and the relay would operate as a sensitive overcurrent relay.

### MULTIPLE RESTRAINT RELAYS

Schemes have been proposed for obtaining a restraining winding for each circuit connected to a bus. One of these is to build a relay with numerous restraining elements operating on a common shaft. This method is undesirable from the standpoint of added complexity and practical considerations. For example, if six or more restraining elements are made to operate on one shaft, the length of the shaft becomes unwieldy and serious mechanical problems are introduced. The same results may be achieved by applying two or more ratio differential relays having three restraining windings and so connected that one restraining coil is available for each circuit and both relays must close their contacts to complete the tripping function. For many applications the standard three-element ratio differential relay, such as the type *CA*-4, is satisfactory. An illustration of this scheme is shown in figure 4 for a bus having six lines connected to it. Each circuit has a separate restraining winding and the operating coils of the two relays are connected in series so that on an internal fault both relays will close their contacts.

For more complex bus connections the same scheme can be amplified using three or more relays per phase, but usually a maximum of three relays is all that is required, since careful consideration of the minimum number of sources that can be connected to the bus at any one time will allow the paralleling of certain current transformers. This means that for all possible bus setups at least two restraining windings will be energized on through faults. For example, operating conditions may be such that for a time no sources of current are connected to the restraining windings of one of the two relays. Upon the occurrence of an external fault this relay would then probably close its contacts. The other relay, however, would have its restraining windings energized in accordance with the current flowing from the active sources to the fault so that its correct performance in failing to close its contacts during an external fault would prevent a false tripping operation.

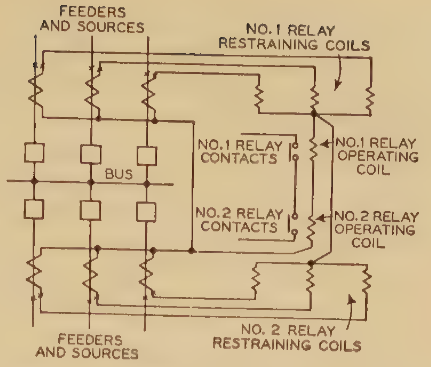

FEEDERS AND SOURCES
NO. 1 RELAY RESTRAINING COILS
NO. 1 RELAY CONTACTS
NO. 1 RELAY OPERATING COIL
BUS
NO. 2 RELAY CONTACTS
NO. 2 RELAY OPERATING COIL
FEEDERS AND SOURCES
NO. 2 RELAY RESTRAINING COILS

**Figure 4. Differential protection using two CA-4 relays per phase**

### VARIABLE RATIO CHARACTERISTICS

The problem becomes more involved if the ratio of maximum through fault current to minimum internal fault current is large. For example, if the system is grounded through an impedance, the operating coil current may be quite limited for a phase-to-ground fault on the bus. If the magnitude of this current in per cent of normal load current is small, a high-sensitivity relay will be required (high sensitivity being synonymous with low percentage ratio). Upon the occurrence of an external interphase fault, however, the current will not be limited by the grounding impedance. If unfaithful current-transformer performance results from these higher currents, it is quite likely that the difference current in per cent of the through or restraining coil current may be high enough to cause the relay to trip. It is obvious from these considerations that the ideal relay for this application should have a variable ratio characteristic. Its percentage ratio should be low at normal currents to furnish sensitive operation for minimum internal faults. Its percentage ratio should be high, correspond-

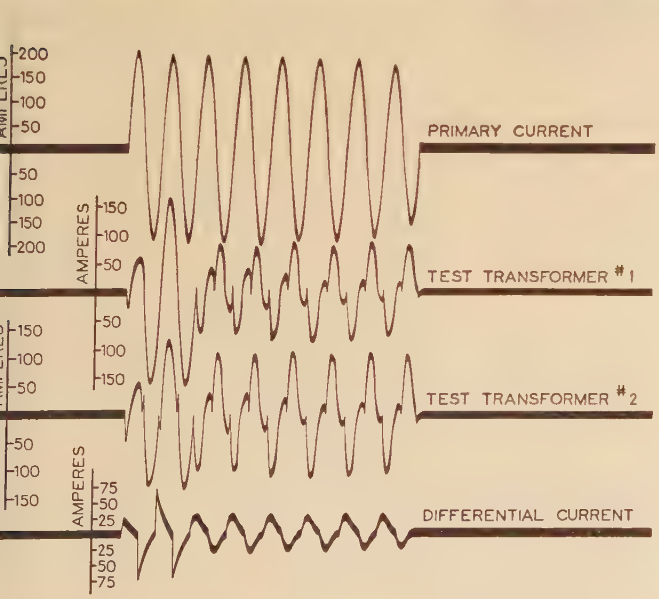


**Figure 3. Oscillogram showing effect of a-c saturation and reversal of one current transformer**

ing to reduced sensitivity, at the higher fault currents to prevent false tripping on through faults. A relay having a variable ratio characteristic is now available. The operating characteristic curve of this relay is not a straight line such as is usually connected with the ratio differential relay, but has a bent or "flared" characteristic. Typical curves for this relay are illustrated in figure 5.

The ordinary remedy of providing a sensitive ground relay together with less sensitive phase relays is not the universal answer to the above problem, particularly where d-c transients are involved. In such an application, the occurrence of an external three-phase fault will result in maximum, or very nearly maximum, d-c component in at least one of the three phases. The current transformers in this phase will saturate more severely than those in the other two phases receiving less d-c component. The resulting unbalance in the secondary currents will flow through the ground relay circuit, and thus tend to cause false operation of a sensitive relay.

The problem of securing the flared characteristics, as illustrated, is quite involved in a multirestraint relay where the torques vary approximately as the square of the current. In the standard type *CA*-4 relay there are three restraining windings and one operating coil winding which have been so proportioned on their respective electromagnets to give approximately straight-line characteristics. It would appear, on first sight, that in order to bend the straight-line characteristic it would only be necessary to increase the turns on the operating coil to increase the sensitivity of the relay at low restraint currents, and then allow the operating element to saturate in order to obtain lower sensitivity at higher fault currents. Such would be the case provided that the particular restraint conditions could be chosen and held constant, which they obviously cannot be. For example, if 60 amperes secondary were involved in a through fault and this current was equally divided between the three restraining windings, the torque per restraining element would be proportional to $3(20)^2 = 1{,}200$. On the other hand, if the current were divided between two restraining windings, 30 amperes in each, the restraining force would be proportional to $2(30)^2 = 1{,}800$. If the total secondary current flows in only one restraining winding, the torque would be proportional to $1(60)^2 = 3{,}600$. Obviously, there is a vast amount of difference between these three quantities themselves and between them and a host of other conditions which may be set up involving various unequal distributions of restraining-coil currents. The problem is also complicated by the fact that the restraining elements themselves tend to saturate at the high currents in a reasonable relay design so that the torque per element departs from the square law at the high currents. This explains why it was found that while the relay characteristic could be bent quite sufficiently for the conditions of maximum restraint by simple saturation, the same bend in the curves did not apply for conditions giving minimum restraint.

## A New Bus Differential Relay

The fact that either one, two, or three restraining circuits per relay might be energized, and thus cause the above variations, led to the development of the type *CA*-6 relay in which no less than two restraining elements could ever be energized regardless of variation in system connections or location of the fault (figure 8). The internal arrangement of the restraining circuits of this relay is shown in figure 6. It is this particular modification of the standard three-restraining-element ratio differential relay which gave the bent operating curves of figure 5. It may be seen from inspection of figure 6 that if current flows in only one of the restraining circuits of this relay, at least two of the restraining electromagnets are energized. This is accomplished by winding each of the restraining elements with two separate windings as shown in the diagram. Current flowing into one of the windings of the restraining element must also flow through the other winding of another restraining element. These windings have an equal number of turns so that they are equally effective.

The polarity marks shown indicate the respective ends of the two windings of a single element into which the currents must flow in order for their effect to be additive. That is to say, two currents of five amperes each flowing into the polarity ends of two windings on one element give the same effect as ten amperes flowing in only one of these windings. At the same time, if a current of five amperes flows in at the polarity mark of one winding and another in-phase current of five amperes flows in at the nonpolarity mark of the other winding on the same element, the net resulting effect is one of cancellation and no torque is produced.

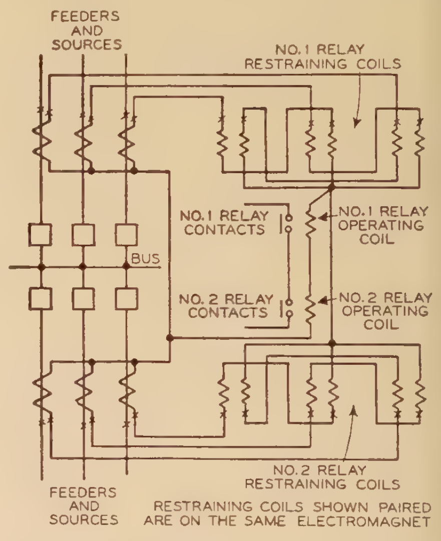


**Figure 6. Differential protection using two CA-6 relays per phase with double restraining windings**

Referring to figures 4 and 6 for the standard and special relays, respectively, and assuming a total of 50 amperes secondary for the external short-circuit current, this current may be divided in numerous ways between the circuits indicated. By assuming a torque proportional to the square of the current in each of the restraining windings for both the standard and the special relay, it will be found that there is considerably less variation in restraining torque between minimum and maximum conditions for the special relay than there is for the standard relay. This feature made it possible to follow the approach mentioned

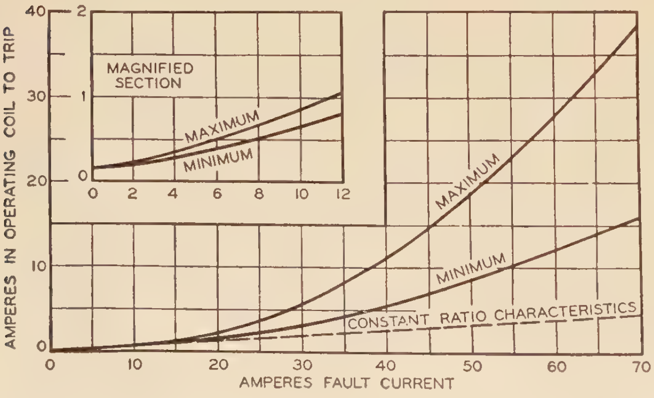


**Figure 5. Operating characteristics of variable-ratio type CA-6 relay**

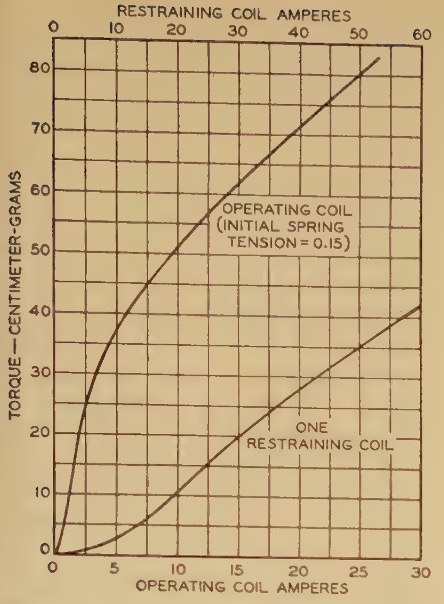


**Figure 7.** Torque-current curves of variable-ratio differential relay

previously which involved increasing the turns of the operating element to increase the sensitivity at low values of restraint current, and to obtain reduced sensitivity at the higher restraint currents by allowing the operating element to saturate. The reduction in variation between maximum and minimum conditions of restraint made possible a smaller variation between the operating curves at the higher restraint values, as shown on figure 5.

The torque curves shown in figure 7 indicate torque in centimeter-grams of the operating coil for various difference or operating currents and the torque per winding of each restraining element for various restraining currents. These torque curves may be used for constructing the operating characteristic of the relay for any particular division of restraining coil currents which may be chosen. Actually, in obtaining the operating curves shown, data were taken for seven different conditions intended to represent all possible divisions of a given fault current with respect to the restraining circuits and with respect to the direction in which this current might flow. It was found that test curves for any one of these conditions could be reproduced by calculated curves obtained by the use of the torque data of figure 7. Thus, the percentage ratio of the relay may be calculated for any given set of conditions. It will be found that the calculated ratio for any condition will fall between the limits indicated on figure 5.

The maximum condition of figure 5 is incurred when the fault current of indicated value flows in one restraining circuit only and flows out of the relay through the common connection to the other relay. The minimum condition shown represents two equal currents flowing into the relay in two restraint circuits and flowing out of the relay through the remaining restraint circuit without any current coming through the common connection to the other relay. In this case, the abscissa represents the total fault current, which is the sum of the two equal and smaller currents.

The time of operation of the relay may be as low as four cycles for internal faults based on one-fourth inch contact travel. A somewhat shorter operating time can be obtained with a correspondingly smaller contact separation.

## System Tests

### System Conditions

Tests on the relay, which has been described, were made under conditions similar to those that would exist if it were installed to protect a 66-kv bus at a large generating station. Conditions simulated were as shown in figure 9 and consisted of five sources representing supply from four transformer banks and a bus-tie breaker, and four transmission lines. The current transformer for only one of these four lines was used, since it was assumed that a fault would exist on only one of the lines at a time. Maximum symmetrical currents for a feeder fault are shown, as well as the cross-sectional area of the current transformers in the various locations, and the manner of connecting them to the relay coils.

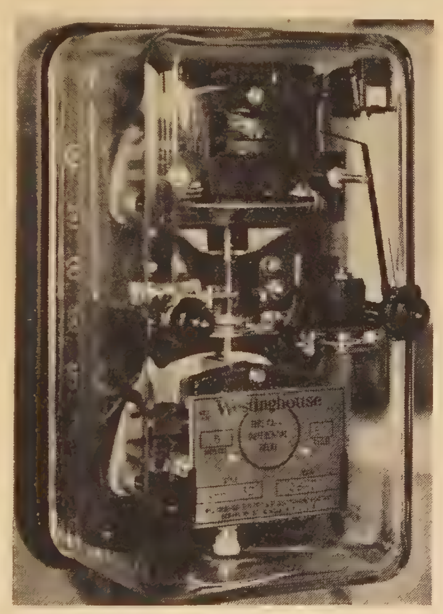


**Figure 8.** Type CA-6 relay

## Test Setup and Test Procedure

Because of the extremely high fault currents (21,000 amperes at 66 kv) it was undesirable to make the tests under actual conditions. The method used is shown on figure 10 in which the current transformers, instead of operating on 66-kv current received 11-kv current, thereby reducing the necessary test current to one-sixth. The test current was further reduced by winding additional primary turns through the bushing-type current transformers. By this means, it was possible to so arrange the number of turns through the current transformers to correspond to the amount and division of fault current from the various sources involved, and at the same time keep the values of fault current well below the full-load rating of the equipment being used for tests. Reversing switches were used in the secondaries of the current transformers so that it was possible to represent both bus faults and through faults in various locations.

Figure 9 shows the bus setup, fault currents, and relay connections for one particular condition. By means of the switches mentioned above, and by varying primary turns in the current transformers, other operating conditions involving different bus connections, different magnitudes and distribution of fault current, and different fault locations were simulated.

Since the time required for the d-c component to decay is a function of the inductance and resistance of the circuit, it was necessary for the test circuit to have a time constant similar to that which would exist during actual fault condi-

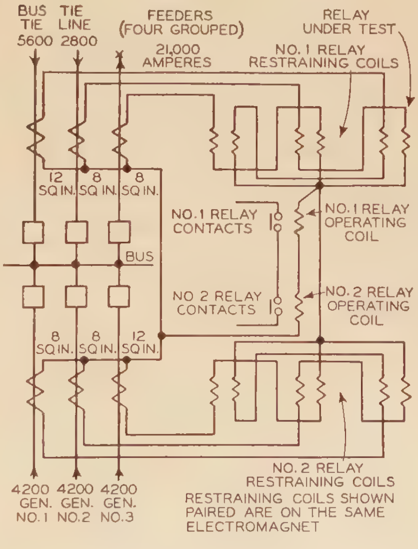


**Figure 9.** Approximate symmetrical fault currents from sources, and sizes of current transformers

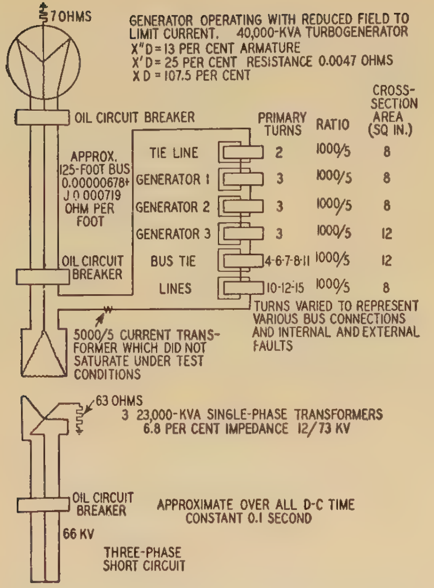

7 OHMS
GENERATOR OPERATING WITH REDUCED FIELD TO LIMIT CURRENT. 40,000-KVA TURBOGENERATOR
X″D = 13 PER CENT ARMATURE
X′D = 25 PER CENT RESISTANCE 0.0047 OHMS
X D = 107.5 PER CENT
OIL CIRCUIT BREAKER
PRIMARY TURNS
RATIO
CROSS-SECTION AREA (SQ IN.)
APPROX. 125-FOOT BUS 0.00000678+ J 0.000719 OHM PER FOOT
TIE LINE 2 1000/5 8
GENERATOR 1 3 1000/5 8
GENERATOR 2 3 1000/5 8
GENERATOR 3 3 1000/5 12
BUS TIE 4-6-7-8-11 1000/5 12
LINES 10-12-15 1000/5 8
OIL CIRCUIT BREAKER
TURNS VARIED TO REPRESENT VARIOUS BUS CONNECTIONS AND INTERNAL AND EXTERNAL FAULTS
5000/5 CURRENT TRANSFORMER WHICH DID NOT SATURATE UNDER TEST CONDITIONS
63 OHMS
3 23,000-KVA SINGLE-PHASE TRANSFORMERS 6.8 PER CENT IMPEDANCE 12/73 KV
OIL CIRCUIT BREAKER
APPROXIMATE OVER ALL D-C TIME CONSTANT 0.1 SECOND
66 KV
THREE-PHASE SHORT CIRCUIT

**Figure 10. Diagram of current-transformer test circuit**

tions. Constants of the test circuit as well as the current transformers used with their approximate cross section of iron, and their turn ratios, are shown on figure 10. The d-c time constant of the circuit was approximately 0.10 second.

The question was raised as to whether the time constants of the generator operating at reduced field would be the same as when operating at normal field. Conclusions were that neither the position of the field rheostat nor the value of the field current would affect the d-c time constant. The a-c time constants would be somewhat affected by the position of the field rheostat. However, by lowering the field current by reducing the voltage of the exciter and leaving the field rheostat in the position corresponding to full-load voltage, the time constants would be approximately the same as at full field. These conclusions were borne out by the results shown on the oscillograms that were taken. The generator was operated at reduced field current (40 to 50 amperes) and approximately 2,500 volts, compared to 230 amperes field current and 11,500 volts for no-load open-circuit voltage. This value of field current supplied approximately 1,400 amperes in the 12-kv leads for a symmetrical three-phase short-circuit fault.

Current-transformer ratios were all 1,000/5. There was a one-ohm resistance burden imposed on each current transformer. This is considerably larger than would normally be met with in practice, but was made large in order to determine, if possible, the limitations of this relay.

A total of 32 faults were applied. This was done by first closing the 12-kv oil circuit breaker, thus energizing the transformer bank, and then closing the 66-kv oil circuit breaker.

Oscillograph records were taken of the currents in the relay coils, as well as the exchange of currents between the two relays. During the tests only one relay was in use, the second relay being represented by dummy coils. Figure 11 shows an oscillogram taken during an asymmetrical through fault; figure 12, a symmetrical through fault; and figure 13 an asymmetrical inside fault.

As observed by the reference to figure 10 the tests were made on a single-phase basis. In order to make sure that the worst asymmetrical or symmetrical condition, whichever was desired, was obtained, it was necessary to make a number of tests under each fault condition. It was found from the oscillograph films that by making four to five tests, there was good probability of the fault current in one of these tests being completely offset.

## Results

Figure 11 shows the oscillographic record of a test made under conditions simulating the operating conditions shown on figure 9. The latter figure shows the location of the fault, as well as the number of sources connected to the bus, and the amount and direction of the current flowing in the various current transformers. It will be observed that the primary current wave, figure 11, is completely offset, indicating maximum d-c transient. This wave represents a faithful reproduction of both the a-c and d-c components of the primary current, and was obtained by the use of a high-ratio current transformer shown on figure 10, which did not saturate on the current values used. It will also be observed that the current waves from the current transformers in the bus tie, tie line, and outgoing line circuits are not faithful reproductions of the primary current. It is obvious that neither the d-c component nor the a-c component represents the true values. This is caused by the saturation of the current transformer cores by the d-c component. Also, the current wave representing the sum of the currents to the other relay from the other current transformers of figure 9 shows the same effect. In all cases, the first peak comes through fairly well, after which the current-transformer performance is far from perfect. Since all the current transformers involved in the differential circuit do not saturate at exactly the same time, nor to the same degree, a difference or operating-coil current results as shown.

Visual observation of the relay indicated that the restraint torque was strong, and there was no tendency for the contacts to close. The contact line on the film, occupying the zero position of the primary current wave, also shows that the contacts did not close. (Closure of the contacts would have deflected this line, as shown on the films representing internal faults.)

Figure 12 shows another test made under exactly the same conditions as for figure 11, except that in this case an almost symmetrical current was obtained. The small amount of d-c component that was present, however, is responsible for the appearance in the operating-coil circuit of the current shown. The magnitude of this current is considerably less than the first peaks shown on the preceding figure, the calibration of the oscillograph element being unchanged. As before, the relay did not operate, but showed a strong restraint torque. In this case, the magnitude of the first cycle of the a-c component of the fault current was measured from the film and found to be approximately 25,600 amperes root-mean-square. From the standpoint of a-c saturation, this test was more severe than the preceding one because of the higher current values, yet it is readily noted that the performance of the various current transformers was much improved.

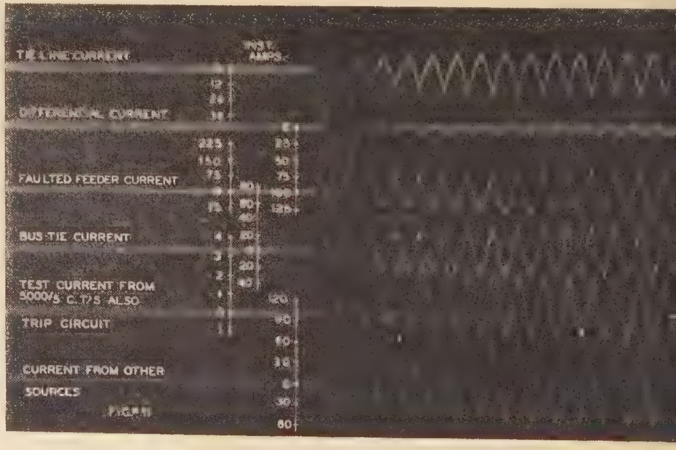


Figure 11. Oscillogram for an external asymmetrical fault

The answer to this is, of course, that in figure 12, the test current transformers are not performing under so severe a handicap imposed by d-c saturation.

A total of 20 tests were made representing through faults under various system conditions and for other magnitudes and distribution of fault current. Both asymmetrical and symmetrical currents were obtained, and, in all cases, the relay showed a strong restraining torque.

Figure 13 shows an oscillogram for a test representing an internal fault on the bus for which the relay should trip. For this test, most of the sources were considered to be on the other bus, so that the bus-tie circuit contributed 19,800 amperes and generator number 3 contributed 7,200 amperes to the 27,000-ampere fault.

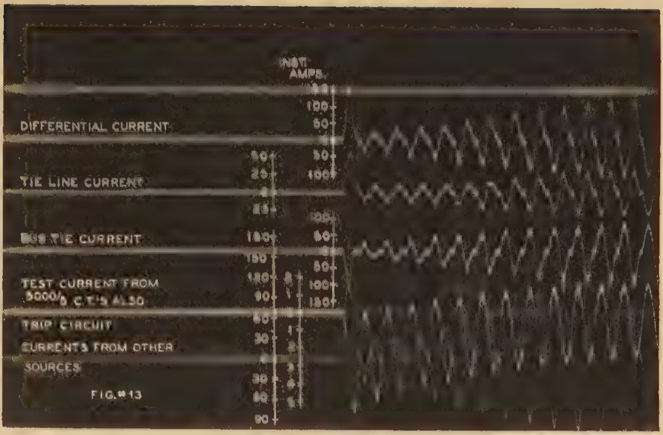
As in figure 11, the effect of the d-c component in causing saturation is immediately obvious. The value of the operating coil current is reduced very materially from the theoretical value, but, by the same token, the restraint-coil currents are also reduced, and positive operation of the relay in a fraction over four cycles is shown. (The jagged contact line shown results from a very small current being used in the contact circuit for the operation of the oscillograph element.)

A total of 12 tests were made representing internal faults under various other system conditions. Both symmetrical and asymmetrical currents were obtained, and, in all cases, the relay operated to close its contacts in a positive manner.

## Conclusions

1. In applying bus differential protection, each application must be considered carefully with respect to the amount and distribution of fault currents, sizes and ratio of current transformers, number of generating sources, and, consequently, the number of restraining coils needed, relationship of protected bus to power sources as affecting the amount and extent of the d-c component, and other important factors.

Figure 13. Oscillogram for an internal asymmetrical fault



2. The use of two or more standard percentage differential relays connected in series as shown in figure 4 makes available the number of restraining coils necessary for most applications.

3. In those cases where a ratio of maximum through fault current to minimum inside fault current is large due to high neutral impedance, relays with special characteristics as described in the paper are available.

4. System tests which simulate the conditions actually obtaining in practice demonstrated the reliability of the scheme and the relay described in the paper.

## References

1. Current Transformer Excitation Under Transient Conditions, D. E. Marshall and P. O. Langguth. AIEE Transactions, volume 48, 1929, page 1464.

2. Relay Protection for Station Busses, W. A. Lewis and R. M. Smith. *The Electric Journal*, November 1937.

## Discussion

**C. D. Hayward** (General Electric Company, Philadelphia, Pa.): In this paper the authors have described some of the special problems encountered in the application of differential relays to generator bus protection, as distinguished from transmission line bus or distribution bus protection. Briefly speaking these problems may be summarized under two heads as to causes:

First, in old installations it is usually found that the only current transformers already available in the feeder circuits are ones of low ratio. In case of a feeder fault close to the bus these are subjected to currents of many times their rating with the result that a high degree of saturation and consequent breakdown in ratio occurs. In the tests described in this paper the authors have confined their investigations to 1,000/5-ampere current transformers, but more often in practice ratios of 400/5 or 300/5 are found. It is evident that much higher degrees of saturation and consequent greater difficulty in applying a relay of the ratio differential type would have been experienced had current transformers of lower ratio been used. It is highly desirable, of course, from a cost point of view to use the existing current transformers if possible, rather than to install new ones or to rewind the old ones for higher ratio.

The second special problem is that of the long time constant of the d-c component of the current to a fault near the generators, for which the $L/R$ ratio is higher than for a transmission line. It is well known to relay engineers that the steady-state ratio and wave-form breakdown of current transformers on overcurrent is greatly affected by the magnitude of the secondary burden. It is not so widely appreciated that the fidelity of current-transformer response to transient offset primary-current waves is also affected by the burden imposed. The d-c component of the primary wave induces a pulse of direct current in the secondary having a magnitude and rate of decay depending on the secondary burden. By the laws of electromagnetic induction the ampere-turns of the secondary d-c pulse oppose the ampere-turns of the primary d-c component and d-c saturation of the core is produced by their difference. The effect of the secondary pulse is always smaller and more rapidly decaying than that of the primary but approaches it most closely when the secondary burden is a minimum. Hence to reduce d-c saturation as well as to reduce a-c saturation and their effects on the current-transformer secondary-current response it is desirable to keep the burden applied to the current transformers as low as possible.

A year ago at this convention L. F. Kennedy and I presented a paper titled "Harmonic Current Restrained Relays for Differential Protection" which was later published in Electrical Engineering for

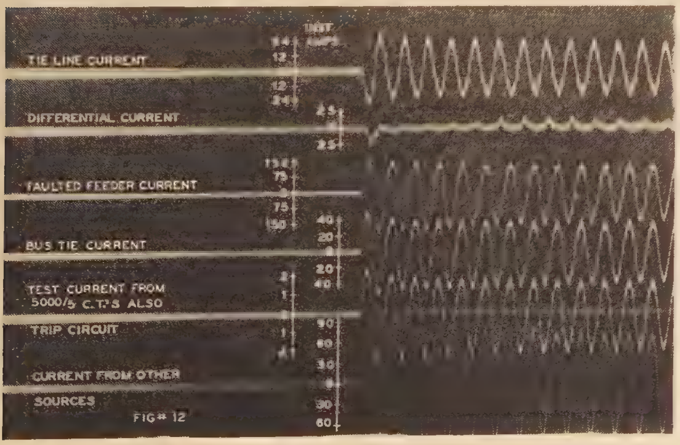


Figure 12. Oscillogram for an external symmetrical fault

May 1938. This paper describes a relay employing filter circuits to separate the harmonic and d-c pulse components of the current presented to it from the fundamental line frequency component, using the fundamental component to energize the operating coil and the harmonic and d-c pulse components to energize the restraining coil. By proper adjustment of the per cent harmonic restraint this relay is made to distinguish between differential currents due to internal faults which contain relatively low percentages of harmonics and those due to current transformer saturation on heavy through faults which contain relatively high percentages of harmonics. This relay is connected in the simple form of differential circuit shown in figure 1 of the present paper.

With this circuit the current-transformer secondaries may be connected directly to paralleling busses in the switchyard resulting in the minimum current transformer burden. Only four wires need be run from the switchyard busses to the relay panel for a three-phase relay setup including ground relays regardless of the number of bus circuits involved.

Compare this with the more complicated circuit for the ratio differential relay in figure 4 or 6. Here a minimum of 19 wires is required for a three-phase setup with only six circuits. Aside from the cost of installing and maintaining the extra wires they are undesirable because of the additional burden which they, together with the relay restraint coils, place on the current transformers.

While high-speed operation may not be absolutely necessary in all generator bus applications it is never undesirable at least and there are many bus applications, transmission busses particularly, where high-speed operation is necessary for stability considerations. While the harmonic-restraint relay has an operating time in the neighborhood of one cycle, figure 13 shows over four cycles for the ratio differential relay. Considerable contact bouncing is also shown by the jagged trace of the contact vibrator. While this would not be serious if only one contact were in the circuit, since contact arcing would probably allow the current to continue to flow after the first contact, it might be serious when two or more contacts each on a separate relay, are connected in series. In this case the circuit is not completed when the contacts close and bounce open alternately but must await a time when all are closed at the same instant. This effect does not show up on the oscillogram because according to the test description, only one relay was actually connected in the circuit, the other being represented by dummy coils.

In conclusion, we believe that for the differential protections of busses as well as other equipment the many advantages of relays employing the harmonic restraint principle should be seriously considered.

**W. A. Lewis** (Cornell University, Ithaca, N. Y.): As discussed in the paper the effect of the d-c transient is the most important single problem in high-speed relaying. This was first forcibly realized in connection with the high-speed relays at Boulder Dam. The problem was given very careful study, for transformer and generator differential relays. It was found that it was relatively easy to predict the design of a current transformer which would not saturate on the d-c transient, but such designs were quite unreasonable to build in a great many cases. In typical cases it was found that the d-c transient has as much as 100 times the saturating effect of the corresponding symmetrical a-c component of the current, that is, 100 times as much flux is required to transform the d-c component accurately as to transform the a-c component. It is thus obvious that the ratio curves of current transformers taken on symmetrical current, even as high as 20 times normal, are entirely unsatisfactory for predicting the performance when the wave contains the maximum amount of d-c transient. In the case of Boulder Dam, the maximum symmetrical short-circuit currents on external faults were limited to three or four times the normal current, and in this case it was possible to obtain a solution by the use of special current transformers.

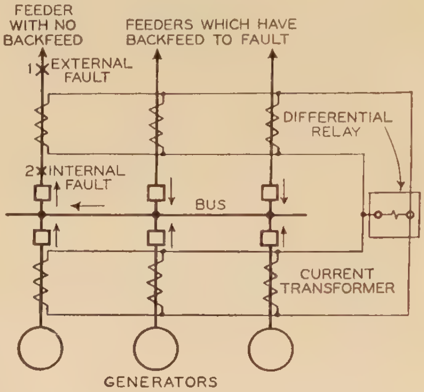


**Figure 1. Schematic diagram of bus differential protection**

However, suitable transformers were found to be four or five times as large as conventional transformers, and it was obvious that this method of procedure was entirely impracticable when the short-circuit currents or external faults are very much larger than the values encountered in this case.

It should, of course, be realized that the effect of the d-c transient is dependent to a large extent upon the rate of decay of the transient, or in other words upon the d-c time constant. This time constant is relatively long when the short circuit is near to high-capacity generating stations, but is reduced very rapidly as the resistance of the circuit is increased by the resistance of transmission circuits. Thus, danger from d-c transient effects is most pronounced in the immediate vicinity of large generating stations, and is almost nonexistent at distribution substations remote from the source of generation.

For any bus differential scheme to operate, it is essential that the current transformer carrying the fault current to an external fault be reasonably good. In the most extreme case, it may be visualized that a current transformer may saturate so severely that the secondary current is zero. When this is true, it is not possible to distinguish between an external fault and an internal fault, and no scheme of bus differential protection can possibly operate satisfactorily. This may be illustrated by reference to figure 1 of this discussion. Assuming first an external fault at the location marked 1 on the diagram, it will be seen that all the fault current must pass through the current transformer in the outgoing feeder. To simplify the problem, it has been assumed that there is no source of power at the other end of the feeder, so that no current will be fed back from the feeder into the fault. If it is assumed that the outgoing current transformer saturates completely, so that there is no secondary current, the current in the differential relay will be exactly the same as it would be for an internal fault at the location marked 2 on the diagram. Obviously, the relay should not trip for the external fault and should trip for the internal fault, so that satisfactory discrimination depends entirely upon the action of the current transformer in the feeder considered. It is thus obvious that the first consideration must be given to the current transformer, and the relay used must be designed to take the best advantage of the current-transformer characteristics. The authors of the paper have given very careful consideration to this problem, and have shown what can be done when each different condition is carefully considered.

Other schemes of bus differential protection which appear simpler have been proposed. However, as pointed out above, none of these can be successful if the current transformers are inadequate. In considering any scheme which makes use of departures of the wave form from a sine wave, it must be recognized that, at extremely high saturations, an iron-core current transformer approaches an air-core current transformer and, for such a case, the output current will again be very nearly sinusoidal, even though it is much less than the nominal ratio of the current transformer would indicate. In applying any such relay scheme, the characteristics of the output wave and the relay must be carefully analyzed, to make certain that the proper requirements for satisfactory operation are fully met.

It is obvious that the burden of the relay has an effect upon the operation of the protective scheme, and the smaller the burden the less the saturation will be in all the current transformers. However, it has been found that, in current transformers of ratios 2,000/5 and higher, the internal burden of the current transformer secondary winding is usually much greater than that of any of the relays proposed, and as a result the burden of the relay used is relatively unimportant in the determination of the current-transformer characteristics. Thus, while low burden is helpful, it becomes a matter of relatively small importance where the current transformer ratio is high, and therefore the desirable relay characteristics should not be sacrificed in an effort to make the burden extremely small. On the other hand, where the current-transformer ratios are 1,000/5 and lower, the internal burden of the current transformer is considerably smaller and more effort is justified in reducing the relay burden.

**T. W. Trice** (Consolidated Gas, Electric Light and Power Company of Baltimore, Md.): The authors of this paper are to be congratulated on the manner in which they thoroughly cover the major factors to be considered in bus differential protection. The way in which the conventional *CA*-4 relay has been modified is unique and its variable-ratio characteristics should make this relay particularly adaptable where there is considerable variation between minimum bus faults and maximum through faults.

Where the ratio of maximum through fault current to the minimum internal fault current is not large and two standard *CA*-4 relays could be used to cover all operating conditions, would it not be possible to use one of the modified relays connected as a simple ratio differential relay having six restraint windings?

It has been noted that the time of operation of the modified relay may be as low as four cycles based on one-fourth-inch contact separation and a somewhat shorter operating time can be obtained with a smaller contact separation. Assuming the smallest contact separation consistent with reliable performance approximately what would be the fastest operating time?

No mention is made as to whether or not any of these modified relays are in service. As in every case the final test of any piece of equipment is its actual service record and a summary of any operating experience with this modified relay would be of interest.

**C. O. Werres** (General Electric Company, Schenectady, N. Y.): Too much emphasis cannot be put on the fact that the success of differential protection is still very largely dependent upon current-transformer characteristics. This dependence is implied in the second paragraph of the article but it will bear reiteration.

The "faithful current transformer" mentioned is a most difficult but desirable goal. Its attainment involves building what has often been called the "ideal" transformer, that is, one with no errors, or to be more practical, negligible errors, throughout its entire range of performance. With this as a goal, much progress has been made. This, along with several other helpful measures listed below, is gradually improving the effectiveness and reliability of differential and naturally other types of protection:

(*a*). Improvements in current-transformer design.

(*b*). Determination of overcurrent characteristics of current transformers.

(*c*). Considering transformer characteristics when laying out protective equipments, etc.

(*d*). A trend toward lower ratio of fault current to current-transformer rating.

(*e*). Balancing burdens and keeping them at a minimum.

(*f*). Inserting resistance in the differential circuit.

Regarding current-transformer designs, the authors point out the difficulty of obtaining matched characteristics at high inductions from two transformers of the same design. The reason for this is obvious from $B$-$H$ curves on core steels which show a wide spread between maximum and minimum characteristics of a given material. The safest solution then is to avoid saturation as was brought out in the Marshall-Langguth paper. However, in designing standard transformers, some compromise must be accepted as it is evident that nonsaturating transformers to meet every condition would be impracticable. A reasonable specification seems to be to limit the ratio error to five per cent at 20 times rated current with burden $Z$.

In view of proposals to adopt a ring-core construction as a means of approaching the ideal, it is pointed out that recent studies on various core designs show that for some ratings the rectangular core can be as good as, and more economical than, the ring core if the secondary is distributed over all four legs.

**A. T. Sinks** (General Electric Company, Lynn, Mass.): The authors are to be commended for again calling attention to some of the idiosyncrasies of current transformers and for emphasizing the fact that these phenomena must be considered carefully in differential relay applications. There are some points, however, with relation to their proposed ideal relay characteristic which are not quite clear.

The bushing current transformers used in the tests described in the paper had large cross sections of iron, so that the products of the iron cross sections and secondary turns were larger than would be normally encountered with instrument-type current transformers. Many current transformers in use on lower voltage systems will have large errors on asymmetrical current waves even for rather low currents. Therefore, the permissible sensitivity of the relay cannot be selected arbitrarily as it depends upon the faithfulness of reproduction of the fault currents by the current transformers, and particularly by the one that carries the total current to an external fault.

From the oscillograms of test and the authors' statement about four-cycle operation of the relay, it would appear that at least in some of the through-fault tests the only reason the relay did not operate was because it was not fast enough, as the oscillogram, figure 11 shows a large value of differential current for the first two cycles. With a given set of current transformers the period during which this false differential current may exist can be longer at low currents than at high ones. Consequently, the chances of this false differential current persisting long enough to operate the relay may be greater at lower values of primary current. Therefore, again why is a higher sensitivity at lower currents a desirable characteristic?

One of the questions which is frequently asked and apparently not well understood is: "Since the fault is fundamentally with the current transformers, why not build them to work right?" Some comment on this point, therefore, seems in order.

There are at least two ways of attacking this problem which give theoretically ideal results as follows:

1. Use air-cored current transformers with carefully balanced burdens, mutual inductances, and secondary-circuit constants.

2. Put enough iron and copper in the transformers to make them accurate up to the desired overcurrent.

There are, however, practical objections to either of these schemes. In the case of the first method, very careful balancing of the factors mentioned is absolutely essential, making each installation a hand-tailored job. Saturating burdens except in the differential element could not be tolerated. The transformers would be entirely special and would not be satisfactory for other services.

When an attempt is made to design a current transformer along conventional lines to reproduce asymmetrical waves faithfully, the first obstacle encountered is the enormous amount of core flux required to generate the d-c transient component of voltage in the secondary circuit. For instance, in the case of a 100 per cent offset wave, 0.1 second time constant, and 60 cycles frequency, the core flux required for the secondary $IR$ voltage associated with the d-c transient is 37.7 times that required for the a-c component. (D-c flux/a-c flux $= 2\pi f \times$ time constant.) From this the large amount of iron necessary to take care of the d-c component of an asymmetrical wave can be readily appreciated. Nor does reducing the secondary-circuit resistance external to the transformer help beyond a certain point as the large amount of iron means a long length of secondary copper which can only be compensated for by making the cross section of copper large. This in turn requires more iron and so the quantities pyramid.

All this does not mean that it is impossible to design an iron-core transformer to reproduce accurately asymmetrical currents of high value, but it does mean that such a transformer will usually exceed acceptable limits of size and cost.

It would, therefore, seem that a relay of the harmonic-restraint type, which actually takes advantage of the peculiarities of the imperfect but economically feasible conventional transformer, is the most practical solution yet proposed.

**J. A. Elzi** (Commonwealth and Southern Corporation, Jackson, Mich.): This paper brings up the point that the application of relays for bus protection has not been given as much attention in recent years as transmission-line relaying. On the contrary, it is our opinion that bus protection has been given considerable attention but the factors that might cause incorrect operation, and which are very well discussed in this paper, have been recognized, and in many cases it has been found that the hazards involved outweigh the advantages to be gained. This paper and the results of tests contained therein show that these potential sources of incorrect operation are important and, in general, could not be taken care of with the relays available until recently.

The high-speed clearing of bus faults to minimize the damage done due to excessive fault currents is only one of the advantages to be gained. In some stations, it is equally as important to be able to sectionalize the bus in case of a fault so that there will be a minimum of loss of load and generating capacity. The extent to which this can be accomplished by a bus protective scheme is of course contingent on the arrangement of circuits on the bus and the number of sectionalizing points provided.

The results of the tests made with the new percentage differential relays described in this paper would seem to indicate that considerably more reliable operation could be expected from this relay than with some of the types heretofore available. The relatively small amount of current available in the differential circuit for the first few cycles in figure 13 leads to the question as to whether or not the relay would have operated in four cycles as indicated if this current had been further reduced by diversion to de-energized current transformers in parallel with the ones which were supplying this current. It would also be interesting to know how the cross section of the cores of the current transformers used in this test compare with those of standard bushing-type current transformers usually supplied for this service voltage.

**R. M. Smith** and **W. K. Sonnemann:** The authors are gratified that the interest in this problem has brought forth interesting and constructive discussion.

J. A. Elzi contributes a valuable point when he asks if the relay would have operated in four cycles, as shown in figure 13, if the operating coil current had been further reduced by diversion to de-energized current transformers in parallel. The tendency is in this direction because of the fact that those current transformers not subject to current in their primaries will draw an excitation current in their secondaries depending upon the voltage across the operating coils of the relays and the magnetization curves of the current transformers involved. This voltage is distinctly limited, however, by the saturation characteristics of the operating coil circuit. Also, the "dead" current transformers, not being affected by d-c saturation, will be operating on their a-c magnetization characteristics and will draw only a very small amount of current. This phase of the problem should be considered if the number of feeder-circuit current transformers in parallel is very large, and if their ratio is low. The authors feel that the more important consideration of this point occurs when the relays must trip under normal load conditions when a light ground fault occurs on the bus. Under this condition the relay is much more sensitive, as illustrated in figure 5, so that more loss of operating-coil current to "dead" current transformers can be tolerated. Ample safety factor has been found in applications studied to date, but it is felt that this point must not be overlooked.

The cross section of iron in the test current transformers represent typical values for present-day 66-kv oil-circuit-breaker bushings, except that 12 square inches appears to be a little large. No definite standards have been established in this respect, however, so that considerable variation may be found.

Mr. Hayward mentions that the test conditions would have been more severe had lower-ratio current transformers been used, such as 400/5. It is admittedly true that, for a given primary current, and other conditions remaining the same, a lower-ratio current transformer will be likely to saturate more severely. This point has been admirably answered, however, in the discussion by W. A. Lewis in which he points out that reasonable performance must be had from the current transformer in the faulted feeder circuit in order that any type of relay may properly discriminate between an internal and an external fault. As a matter of fact, a relay of the ratio-differential type, having a slight time delay, is less likely to operate falsely with low-ratio current transformers than a relay of the high-speed (one cycle) type. This is because its time delay allows the badly saturated current transformer enough time to recover from d-c saturation sufficiently to discriminate between external and internal faults.

Mr. Hayward makes the point that it is well to keep the secondary burden as low as possible in order to minimize the effect of the d-c transient in saturating the current transformers. If this could be carried to the ultimate end so that no current transformer in any part of the circuit would saturate, then a simple differential relay as indicated in figure 1 would suffice. In the majority of cases, however, where the d-c transient has a long time constant, it will be found practically impossible to escape the effect of d-c saturation in those current transformers in the faulted feeder circuit, even by decreasing the lead burden, as has been pointed out. In this case, when saturation of the output current transformers is assured, it is a definite advantage to have some degree of saturation in the input current transformers as well. For example, in figure 11 of the paper, the traces show definite saturation of the various current transformers in the input leads to the bus. The degree to which the input current transformers fail to hold their ratio makes a corresponding reduction in the magnitude and duration of the differential current.

The statement made by Mr. Hayward that the relative percentage of harmonics present in the differential current is sufficient to discriminate between external and internal faults is somewhat optimistic, in view of the findings on a large number of tests. With sufficient time delay, a material percentage of harmonics will show up in the differential current for an external fault. If time delay is introduced, however, the relay is no longer a one-cycle relay. In figure 2 of this paper, for example, the first two cycles of differential current are obviously notably lacking in harmonics to any great degree. If the relay is sufficiently sensitive to harmonics to be adequately restrained from tripping for the first two cycles of the differential current of figure 2, then there is certainly grave doubt that the relay would trip properly when subject to the differential current wave form of figure 13 of the paper. It may be argued that the lower burden of the relay mentioned would do much toward improving the wave form of figure 13. This is quite true, but, on the other hand, the internal burden of the current transformers plus the burden of the differential circuit leads to the switchyard must still be considered. The experience of the authors is that there is practically an infinite variety of wave forms possible in the differential current, even when some of the variable factors are fixed. For example, the current-transformer characteristics and burden values will be fixed for a particular installation, but the variable location of the fault, involving a variable time constant, as well as variable current values, may be taken in an infinite number of combinations. Thus, it is impossible to say that any one particular wave form is typical of all external faults.

Attention has been called to the broken nature of the contact line of figure 13. It should be borne in mind that for these tests it was only desired to get a contact indication, and not to trip any breakers. The current through the contact circuit was extremely light, amounting only to that required to operate an oscillograph element, and was thus easily interrupted momentarily. Tests not described in the paper were made to establish the fact that two contacts in series could be made to pick up an auxiliary relay, at 125 volts direct current and four to five amperes, without additional delay, and were entirely successful. The auxiliary relay is necessary, of course, because of the large number of circuit breakers which must be tripped.

The supposition of Mr. Sinks that the only reason that the relay described in the paper did not trip for some of the external faults was because it was not fast enough is not correct. It is true that a large value of differential current existed for at least two cycles; however, a large restraining torque existed at the same time. The restraining torque was considerably in excess of the operating torque for all of the through faults.

Mr. Trice asks if one of the six-circuit special *CA*-4 relays might not be used in an application where two standard *CA*-4 relays would suffice. We interpret this question to mean that, since six restraining coils are available in the special relay, it would seem to be applicable on the basis of one relay per phase for a six-circuit bus. If applied in this way, however, each restraining element would receive current from two bus circuits. If a heavy current should flow into the bus in one of these circuits and away from the bus in the other, the ampere turns on that particular restraining element would be in opposition and thus cancel out. That is, equal and opposite heavy currents in the one restraining element would not produce restraining torque as they should. The same effect exactly would occur if the current transformers of the two paired circuits were paralleled on the secondary side and connected to one single-winding restraining element. In the first case, fluxes are paralleled. In the second case, currents are paralleled. The net effect is the same. These considerations indicate that if six restraining elements are required, then two relays per phase are necessary, whether they be the standard or the special type.

Some gain may be made in shortening the operating time for internal faults by decreasing the contact travel. However, not a great deal can be accomplished by this means. Probably the fastest operating time under most favorable conditions would be two to three cycles.

In answer to Mr. Trice's third question, no relays of the special type having double windings and variable-ratio characteristic have yet been placed in service, although some are now on order.

# Copper-Oxide Modulators in Carrier Telephone Systems

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**Synopsis:** Copper-oxide modulators are widely used in telephone systems for translating either single speech channels or groups of speech channels to carrier-frequency locations on the lines. A number of simple circuit arrangements have been developed that enable suppression of certain undesired frequencies to a degree that is impractical in tube modulators. These modulators transmit equally well in either direction and the modulating elements are more nonlinear than in tube modulators. As a result numerous effects are found that ordinarily are not important in the tube arrangements. Analytical studies have been considerably simplified by the use of a small signal, and a large carrier controlling the impedance variation of the copper oxide. It is found in this case that the superposition and reciprocity theorems hold for all the circuits that it has been possible to analyze even though the modulator is made up of nonlinear elements. Open and short-circuit impedance measurements can be made use of as in four-terminal linear networks, and a generalized reflection theory developed. Performance data are given for an idealized modulator under a variety of operating conditions.

AT LEAST as early as 1927, copper-oxide rectifiers were being tried as modulators for the speech channels of carrier telephone systems in this country. At this time only a rather large type of rectifier was available, better adapted for power use rather than in modulating the few milliwatts of a speech signal. Largely because of instabilities these early units were found to be unsatisfactory for modulator use. Further developments in copper-oxide rectifiers made in various laboratories extended the variety and improved the quality of the product available, so that by about 1931 they began to be promising as serious competitors for vacuum tubes in modulators. Since 1931 continued improvements in copper-oxide rectifiers have rapidly increased their field of application until now they are employed in practically all modulators of the latest types of carrier telephone systems.

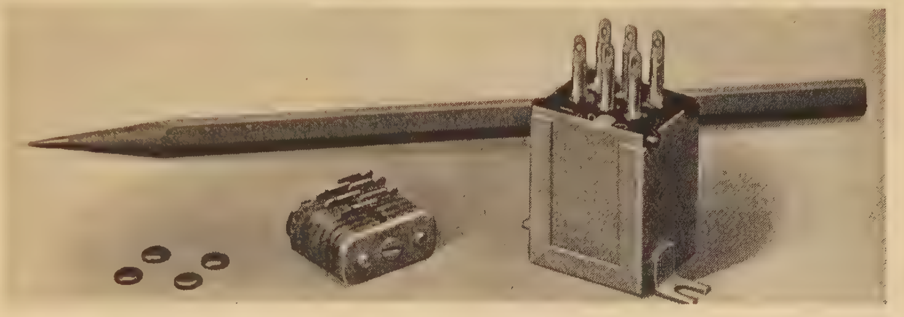

Figure 1. Four-disk copper-oxide modulator

In the new systems a copper-oxide modulator is used instead of the previous push-pull arrangement of two vacuum tubes. In cable,* open-wire, and coaxial carrier systems, from 26 to 28 of these modulators are needed in each direction for translating each 12-channel group of speech bands from voice to carrier and back again. These copper-oxide modulators have no power costs, tube replacements, or possibilities of power failures. In figure 1 the four $^3/_{16}$-inch-diameter copper-oxide disks generally used in a carrier telephone modulator are shown individually, assembled with connections, and potted in a can.

The carrier terminals have tended to become increasingly complex as it became their function to place more and more channels on a single pair of wires. The extreme simplicity and reliability of copper-oxide modulators have been of great value in helping to overcome this tendency. Copper-oxide modulators have been used from zero frequency to nearly four million cycles. Certain modulators for coaxial carrier systems have been designed to modulate simultaneously as many as 60 speech channels spaced over a 240,000-cycle band of frequencies.

Copper-oxide modulators probably differ most from tube modulators because the simplicity of the rectifier elements allows a much greater variety of circuit arrangements to be used. Although the underlying principles of operation are not new, it has become necessary to investigate numerous transmission effects that could be neglected in tube modulators. This has resulted not only from the newer circuit arrangements with their smaller losses, but also from higher transmission standards for the over-all system along with the greatly increased numbers of modulators in long circuits. Copper-oxide modulators, unlike tube modulators, transmit signals equally well in either direction. While this is a simplification in allowing a modulator also to be used as a demodulator, the modulator becomes complicated by the effects of reflections back and forth into the signal bands of numerous frequency bands of modulation products.

## Circuit Arrangement

The circuit arrangements used in copper-oxide modulators generally are concerned either with carrier suppression, with carrier transmission along with the signal, or with balancing action to suppress certain unwanted bands of signal frequencies. In most carrier telephone systems economy of frequency space and amplifier load capacity demands the use of single-sideband carrier-suppressed transmission.

In figures 2*a*, 2*b*, and 2*c* three types of copper-oxide modulators are shown, each arranged to suppress the carrier in both the signal input and the signal output circuits. In figures 2*d* and 2*e* the carrier is balanced out in only one signal branch. In the usual arrangements a signal-band selective filter must be used in each signal branch to restrict transmission to that of the wanted frequency band. Largely in this way interferences are guarded against, not only into other channels or systems to which the modulator output circuit is connected on the line or at the distant

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* The general features of carrier telephone terminals have been described in a paper "Cable Carrier Telephone Terminals," by R. W. Chesnut, L. M. Ilgenfritz, and A. Kenner (Electrical Engineering, January 1938).

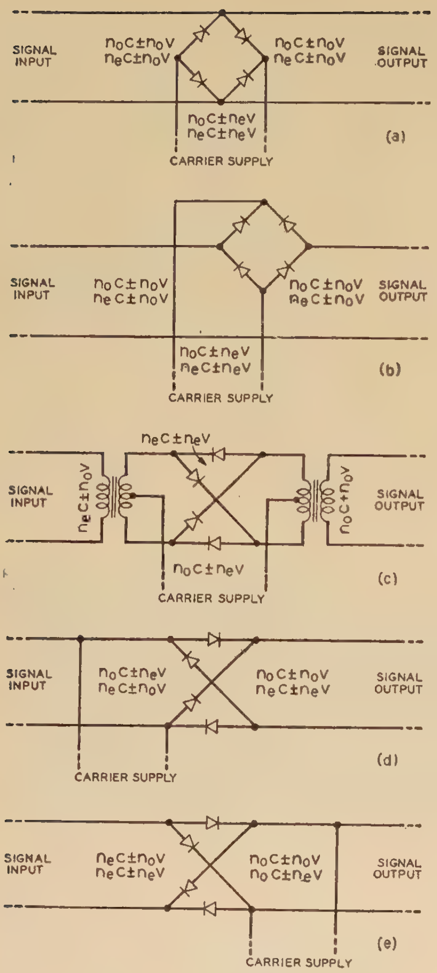
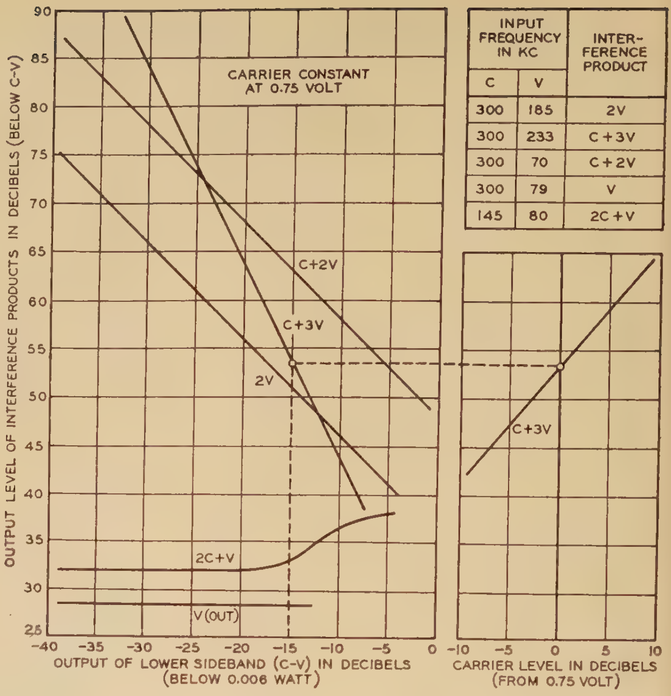


**Figure 2 (left).** Types of copper-modulator oxide circuits



| INPUT FREQUENCY IN KC | | INTERFERENCE PRODUCT |
|---|---|---|
| C | V | |
| 300 | 185 | 2V |
| 300 | 233 | C+3V |
| 300 | 70 | C+2V |
| 300 | 79 | V |
| 145 | 80 | 2C+V |

**Figure 3.** Intensity of modulation products in a representative double-balanced copper-oxide modulator

end, but also back into the complex array of facilities to which the input circuit may be connected.

In any of the circuits shown, modulation results from either the reduction or reversal of the current flow between the input and output signal circuits at periodic intervals as the carrier varies the copper-oxide resistance back and forth between high and low values. In figure 2*a* where the connections of the input and output signal circuits are periodically short-circuited by the carrier-actuated copper oxide, transmission of the modulated signal into the input circuit or the unmodulated signal into the output circuit is prevented by filters, each of high impedance at the frequency of the other signal. In figure 2*b* the connections between the signal and modulated signal circuits are open-circuited periodically by the carrier. In this case each filter should have a low impedance at the other signal frequency. In figures 2*c*, 2*d*, and 2*e* the copper-oxide rectifiers are made to become alternately low and high resistance in pairs as the polarity of the carrier is either in the same direction as the arrows or in the opposite direction. As a result current flow from the input signal circuit into the output is periodically reversed by provision of a periodically reversing low-impedance path. In effect each signal is balanced from the other's circuit.

Although an indefinite number of other circuit configurations can be used, no novel transmission feature would be found which was not present in the five circuits already shown. Third order modulators in which the copper oxide is arranged to give equal interruptions to the signal in both positive and negative half cycles of the carrier are exceptions not considered here. In addition, circuits like Hartley's, in which phase discriminations have been obtained in the sideband outputs from two modulators by altering both the carrier and signal input phase of one, can be viewed as composed of two modulators of any of the types illustrated.

In these copper-oxide modulators all modulation product frequencies can be grouped into four classes:

$n_oc \pm n_ov$
$n_oc \pm n_ev$
$n_ec \pm n_ov$
$n_ec \pm n_ev$

in which $c$ and $v$ are the carrier and input signal frequencies and $n_o$ is any odd number 1, 3, 5, etc., while $n_e$ is any even number 0, 2, 4, 6, etc. If $c$ and $v$ contain more than one frequency each, $n_o$ and $n_e$ are, respectively, the odd and even combinations of all multiples of the $c$ and $v$ frequencies. All frequencies of one of these four types appear together in a specific branch of the modulator circuit; and they will not appear in another branch unless from a dissymmetry among the copper-oxide units or unless inherent in the circuit configuration. The branches in which the modulation products appear are shown in the circuits illustrated. It is apparent that only in the case of the double-balanced circuit of figure 2*c*, are all of these types of products completely separated in different parts of the circuit. In the other circuits shown the classes of products appear together in combinations of two types. In any balanced circuit that can be drawn the above relationships will be found to hold.

Modulation products will be of a type to which the circuit offers some degree of balance, of a type that can be made to vary in importance relative to the signal by adjustment of either the carrier or signal voltage, or of a type to which neither balance nor level adjustment is of any benefit. Satisfactory operation of such modulators requires large carrier voltages relative to those of the signal, so that products like $c \pm v$, $2c \pm v$, $3c \pm v$, etc., tend to be of large magnitude while products like $c \pm 2v$, $c \pm 3v$, etc., tend to be small. Furthermore, the former types can be made to predominate even more over the latter types either by increasing the carrier amplitude or by decreasing the signal levels. A 6-decibel reduction in signal results in 12-decibel reduction of $c \pm 2v$ and 18-decibel reduction in $c \pm 3v$. In any circuit application interferences of this type lend themselves to reduction in so far as carrier power is available for high-signal-level operation, or in so far as noise does not limit for low signal levels. Laboratory measurements of some of these modulation products made during the development of a group modulator for a 12-channel open-wire carrier system are shown in figure 3 for a double-balanced modulator like that of figure 2*c*. Single $^3/_{16}$-inch-diameter disks as shown in figure 1 were used in each bridge arm. About 20 to 30 decibels reduction in interference by balance alone is quite readily obtained in the normal run of manufactured copper-oxide rectifier elements, for those products to which the circuit arrangement offers a balance. Any further improvement must be obtained either by closer control of manufacture or disk selection, by artificial balancing with some means such as capacitor-resistance potentiometers, or by statistical averaging through use of numbers of disks in each bridge arm.

In single-channel modulators interferences caused by the signal into its own signal band will occur only in the presence of the signal. In such cases they need be only 20 to 30 decibels below the signal, except in special cases, as for example, modulators for broad-band program channels. In multichannel systems interferences may be produced in the silent channels by the active channels. This kind of interference or crosstalk is ordinarily made to be 70 decibels or more below the wanted signals for commercial telephone service. In such cases overlapping bands of frequencies not improved by level adjustment are avoided by judicious choice of the carrier frequencies.

## Circuit Impedance and Loss

In all modulators the carrier serves merely as a means for obtaining a simple periodic variation of the impedance presented to the signals. It is not only immaterial to the signals how this variation is obtained, but the signals also are totally unaware of whether electrical, mechanical, or other means are used, just so long as the signals themselves are unable to affect the time variation of this impedance. In a copper-oxide modulator, only by making the carrier amplitude large compared to the signal amplitudes across the rectifier elements, can the impedance of the rectifiers be made to vary at carrier rather than signal rates. Too large a signal amplitude not only results in the production of undesired frequencies, but also the impedance and loss characteristics of the modulator vary with the signal amplitude. With small signals the carrier energy is used up in maintaining the copper oxide at prescribed impedance values at each instant of time, and none of the modulation products involving the signal receive more than a negligible amount of energy from the carrier. As a result the output signal energy will always be less than that of the input signal, partly because of $i^2r$ losses within the copper oxide, and partly from the diversion of the input signal energy into the energies of the many modulation-product frequencies.

The signal impedance of a copper-oxide modulator is a combination of a characteristic impedance of the rectifier elements and the impedance of the connected circuits at all the modulation-product frequencies. The characteristic impedance of the rectifier can be viewed crudely as an average of the impedance encountered by a small signal over a cycle of the carrier, treating each instantaneous value of the carrier voltage as a d-c bias. If the impedance for small superimposed alternating voltages is measured on a single copper-oxide disk at various direct bias voltages, this impedance generally changes with both bias and frequency. Measurements to 200 kilocycles made on a $^3/_{16}$-inch-diameter disk are shown in figure 4. At all negative bias voltages the impedance is a resistance in parallel with a capacitor. This resistance decreases rapidly with increasing frequency while the shunt ca-

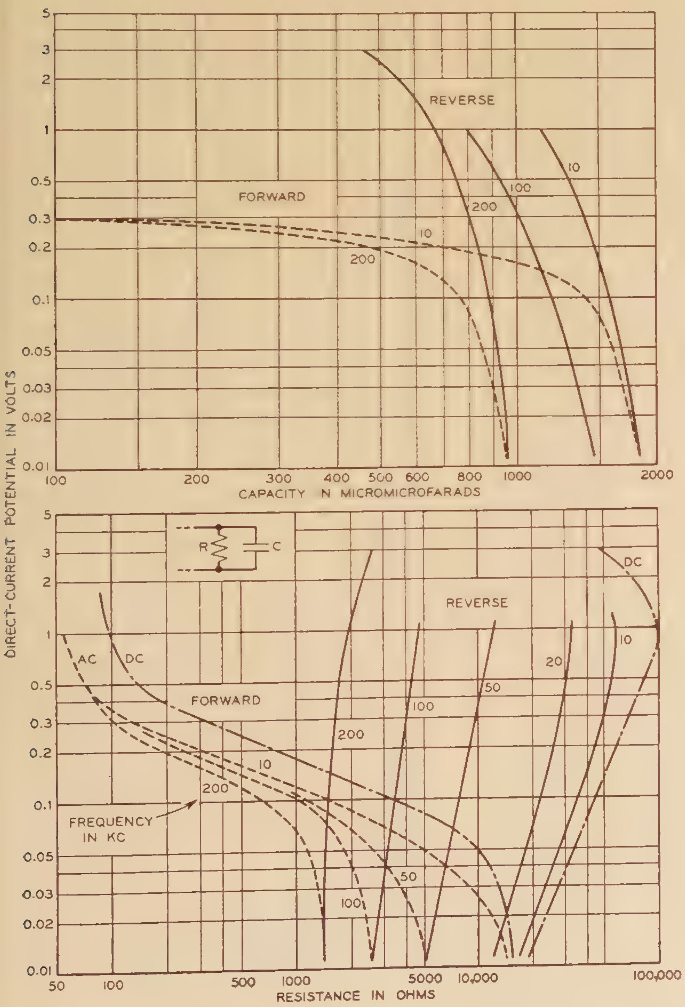
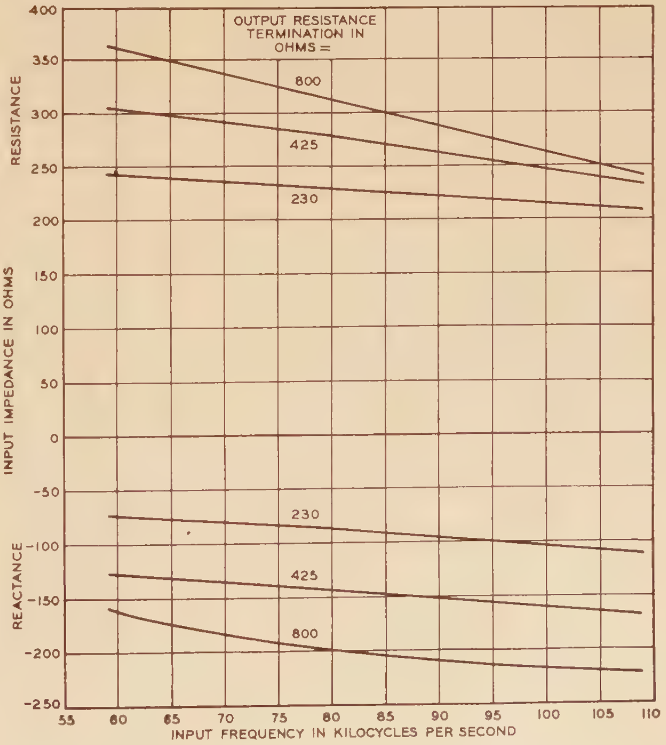


Figure 4. Impedance of a copper-oxide disk at various forward and reverse direct voltages for small superposed alternating voltage

Figure 5. Impedance of a representative double-balanced modulator



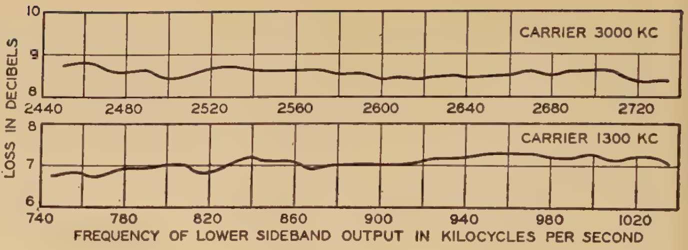
pacity decreases only a moderate amount. At moderate positive voltages (about one-half volt) the impedance becomes resistive and does not change appreciably with frequency. Experimentally it is found that the signal impedances in resistance-terminated modulators can be made largely free of reactance at high frequencies by using either large carrier amplitudes, inductive tuning of the copper-oxide capacities, or lower-impedance-connected signal circuits to accentuate the importance of the low-resistance part of the copper-oxide characteristic. Very much lower circuit impedances must be used at the higher frequencies. Where 600 to 1,000 ohms is a satisfactory impedance at speech frequencies, less than 50 ohms may be the best impedance to use, at three megacycles.

Impedance measurements on a double-balanced modulator designed to translate a 12-channel group of frequencies for cable carrier systems from a band at 60 to 108 kilocycles to a 12- to 60-kilocycle band are shown in figure 5 for several resistance terminations. Absence of any impedance irregularities with frequency is apparent. Also, the tendency is shown for the modulator impedance to become less reactive with lower-resistance terminations.

Inasmuch as copper-oxide disks are available in sizes from $^1/_{16}$ inch to more than an inch in diameter, a wide range of circuit impedances is possible varying from only a few ohms to thousands of ohms Large-area disks roughly are equivalent to small-area disks in parallel. Thus by using a disk of *n* times the area of a small one or *n* of the small ones in parallel, the best circuit impedance becomes 1/*n*th at the same carrier voltage. Either disks in series or ones of smaller diameter enable the impedance to be raised in a corresponding manner. The lower impedance and greater energy dissipations of larger disks, or paralleled smaller ones at the same carrier voltage, obviously allows greater input signal energies before the signal impedance and loss begin to vary with the signal, and overload distortion appears. Similarly series stacks of disks, or series-parallel combinations, offer wide choice in both the signal levels that can be satisfactorily modulated and in the impedance levels. Usually root-mean-square carrier voltages across individual disks in the conducting direction will best be made somewhere between three-tenths and three-fourths volts.

The impedances of the connected circuits at the modulation product frequencies react back on the signal impedances in a way similar to the way that the two terminating impedances of a four-terminal linear network react on each other. In the case of the copper-oxide modulator a reaction from some modulation product back into the signal impedance is less and less as the product becomes of higher order, or as the circuit loss to it becomes greater. Where the impedances of the connected circuits have bothersome interactions with the copper-oxide impedance either at the signal frequencies or the lower-loss modulation products, resistance-pad separation is usually the simplest solution if the increased loss can be tolerated.

**Figure 6. Loss in a double-balanced group modulator for coaxial systems**



Energy losses in copper-oxide modulators between signal input and single-sideband signal output have been found to be no greater than eight or nine decibels even at frequencies of three or four megacycles. At lower frequencies five- or six-decibel losses are normal, but losses as low as two decibels have been obtained under less practical operating conditions. Experimental loss measurements are shown in figure 6 for a double-balanced modulator using single $^3/_{16}$-inch-diameter disks in each bridge arm. This modulator was designed to modulate simultaneously 60 speech channels occupying a 240,000-cycle band width. The modulator loss, like the impedance, depends on the impedance terminations of the modulator at all the modulation-product frequencies as well as on the internal losses of the modulator. Short circuit, open circuit, or reactive terminations at the unwanted frequencies, permit energy losses only through reflections at the signal-circuit junctions to the modulator or within the modulator. With proper terminations and loss-free copper oxide, 100-per-cent-efficiency frequency translations are theoretically possible. In a practical case, a larger carrier amplitude results in a smaller percentage of the time in which the rectifier elements have impedances that are comparable to the connected circuits and that are neither blocking nor conducting. Signal energies are lost in this time interval, so a higher efficiency modulator results. The time spent on the intermediate resistance parts of the rectifier characteristic can be further reduced by introducing harmonics into the carrier wave, so that a square type of wave results. The resistance of the rectifier is abruptly switched back and forth between blocking and conducting values in this manner. When the connected circuit impedances at the unwanted frequencies are very high or low, best efficiencies result when transmission between the signal circuits is blocked most of the time. Thus in a circuit like that of figure 2*a* when the filters are high impedance at the unwanted products, highest efficiency results when the copper oxide is a low-resistance short circuit for the major portion of the carrier cycle. In figure 2*b* an open circuit is desirable most of the time.

## Linear Modulator Theory

The analytical studies that have been of most benefit in the development of copper-oxide modulators have made use of a variable resistance characteristic controlled by the carrier. This assumption has made it possible to investigate modulator performance* for a wide variety of characteristics under a great many operating conditions. Copper-oxide-modulator performance in particular cases as well as the effects of the circuit elements on this performance can readily be inferred from the data at hand about these idealized modulators.

In limited space it is not possible to discuss the varieties of resistance modulators that have been analyzed. However, certain viewpoints will be discussed that have been very useful not only for obtaining solutions for some of the hypothetical cases, but also in supplementing laboratory experiments on actual modulators.

All of these analytical studies have assumed a signal sufficiently small compared to the carrier, that it can be varied in magnitude without noticeable changes in the signal impedance or in the linearity between input and output signal amplitudes. This is in agreement with design procedure, as the circuit impedances and losses are determined on such a linear basis.

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* A physical picture of modulator performance in terms of linear networks is developed in a paper published in the January 1939 *Bell System Technical Journal:* "Equivalent Modulator Circuits," by E. Peterson and L. W. Hussey.

### Superposition Principle

All of the modulator circuits with which we have been dealing, though composed of nonlinear elements, have been resolved into the equivalent of linear systems by virtue of using a large carrier and small signal amplitude. We may simultaneously apply any number of signal frequencies, but all have negligible effect on the periodic changing of the nonlinear element resistance by the carrier. These frequencies may be modulation product voltages, some applied at the output terminals and some at the input terminals, but in all cases, even though frequencies may coincide, it can be shown that the principle of superposition will hold without interaction between the applied forces and the responses. This permits a great simplification in the mathematical approach to modulator analysis, because the modulation product or signal voltages can be applied one at a time and the current responses summed. The voltage-current ratios at each frequency can then be replaced by equivalent impedances.

Any nonlinear resistance like copper oxide will have a current-voltage characteristic that can be expressed as accurately as desired by

$$i = a_1e + a_2e^2 + \ldots a_ne^n \qquad (1)$$

If a carrier and signal voltage are applied to this nonlinear element, each term beyond the first will independently produce currents of new frequencies composed of the intermodulation products of these two voltages. If in turn the external impedances at these new frequencies are not zero, new voltages will appear across the nonlinear element to produce still more new frequencies. In this case the simplest consideration is to minimize the number of voltages by presenting zero impedance to the modulation products. If the carrier voltage is $C \cos ct$ and the input signal voltage $S \cos st$, the current flow in the $n$th term is

$$i = a_n\,(C \cos ct + S \cos st)^n \qquad (2)$$

In the binomial expansion of this expression it is obvious that linear response to the signal and freedom from distortion result when the ratio of carrier to signal is made sufficiently large so that only the first two terms are important.

$$i \approx a_n[(C \cos ct)^n + n(C \cos ct)^{n-1} \cdot S \cos st] \qquad (3)$$

The first term in equation 3 is the current flow at direct current and harmonics of the carrier; it has no effect on the input signal and output signal except in so far as impedance termination presented across the nonlinear element at the carrier harmonic frequencies may alter the carrier-voltage harmonic content. The signal input current and the signal output current, as well as the unwanted modulation products of the signal, result from the second term. The even values of $n$ produce the even-order sidebands, second order being the output signal, while the odd values of $n$ produce the input signal current and the odd-order sidebands. These currents can be evaluated from

$$\cos^n b = \frac{K^n_{\frac{n}{2}}}{2^n} + \sum_{m=1}^{m=n} \frac{K^n_{\frac{n-m}{2}}}{2^{n-1}} \cos mb$$

in which $K^n_{\frac{n-m}{2}}$ is equal to the combination of $n$ things taken $\frac{n-m}{2}$ at a time for $\frac{n-m}{2}$ integral and is equal to zero for $\frac{n-m}{2}$ nonintegral. The signal input current is

$$i_s = \frac{a_nnK^{n-1}_{\frac{n-1}{2}}}{2^{n-1}} C^{n-1}\,S \cos st \qquad (4)$$

while the second-order output signal sideband is

$$i_{c \pm s} = \frac{a_nnK^{n-1}_{\frac{n-2}{2}}}{2^{n-1}} C^{n-1}\,S \cos\,(c \pm s)t \qquad (5)$$

Similarly, if the output signal voltage at second-order sideband frequency $(c \pm s)$ had been applied along with the carrier in place of the input signal, and of an equal amplitude, then the following currents of the output and input signal frequencies would result

$$i_{c \pm s} = \frac{a_nnK^{n-1}_{\frac{n-1}{2}}}{2^{n-1}} C^{n-1}\,S \cos\,(c \pm s)t \qquad (6)$$

$$i_s = \frac{a_nnK^{n-1}_{\frac{n-2}{2}}}{2^{n-1}} C^{n-1}\,S \cos st \qquad (7)$$

If both signal input and output frequency voltages are applied simultaneously, equation 3 then becomes

$$i \approx a_n[(C \cos ct)^n + n(C \cos ct)^{n-1} \cdot S \cos st + n(C \cos ct)^{n-1} \cdot S \cos\,(c \pm s)t] \qquad (8)$$

The current responses obviously are the sum of the separate responses from independent application of the two frequencies. Even if a complex array of terminating impedances are supplied so that voltages appear across the nonlinear element at all the modulation product frequencies, each new voltage will individually produce its own current response, quite independently of the responses that are being produced by the other voltages. It can readily be seen then that superposition does not depend on any assumptions about what the terminating impedances may be.

## Reciprocal Theorem

Equations 5 and 7 show that the sideband response to an input signal voltage is exactly equal in magnitude to the input signal response to the same amplitude sideband voltage. It can readily be seen that any two modulation products also bear such a reciprocal relationship between their voltages and currents, as a result of using the same amplitude and frequency of carrier harmonic multiplier of their respective voltages to modulate between the two frequency positions. Although reciprocity has been proved valid here only for short-circuit terminations at the modulation-product frequencies, it can also be proved under numerous other conditions of circuit operation. It seems that, regardless of modulator complexity of impedance terminations or frequency loss effects, *the reciprocal theorem is a necessary attribute of such a linear and bilateral system in which there are no internal energy sources.* Two-way systems in which an amplifier for example, is included as an internal energy source in one or both directions will, of course, violate the reciprocal theorem if the gains in the two directions are different. This arrangement is, however, both bilateral and linear.

### Complete Performance Criteria

The laws for transmission between a signal input frequency and a signal output frequency can be completely specified from open- and short-circuit impedance measurements at the signal input and output frequencies, regardless of the complexity of the modulator. (From such measurements optimum impedance terminations can even be determined for linear-bilateral systems with internal energy sources.)

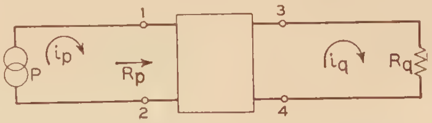

**Figure 7. Four-terminal network equivalent of a linear modulator**

The four-terminal network of figure 7 is assumed to represent a modulator with a large carrier amplitude and having small signal voltage $P$ of frequency $p$ applied at the input terminals 1–2 at the left. Current of the output signal frequency $q$ flows out of the terminals 3–4 into the impedance $R_q$. The generator $P$ is assumed to have zero internal impedance at its own frequency. Impedance terminations at the 1–2 and 3–4 terminals at all other modulation-product frequencies are perfectly general; whatever they are in a particular case, it is assumed that they are undisturbed as the terminations of the input and output at the signal frequencies are varied between open circuit and short circuit. The following symbols are used for the impedances looking into the modulator at the input terminals at input signal frequency $p$ and at the output terminals at signal output frequency $q$.

$Z_{po}$ = impedance at $p$ for open circuit at $q$
$Z_{qo}$ = impedance at $q$ for open circuit at $p$
$Z_{ps}$ = impedance at $p$ for short circuit at $q$
$Z_{qs}$ = impedance at $q$ for short circuit at $p$
$R_q$ = impedance termination at frequency $q$
$R_p$ = impedance of modulator at frequency $p$ with $R_q$ at 3–4 terminals for frequency $q$
$K_a$ = transfer admittance between voltage at frequency $p$ applied at the 1–2 terminals and short-circuit current at frequency $q$ flowing from 3–4 terminals
$K_b$ = transfer admittance between voltage applied at 3–4 terminals at frequency $q$ and short-circuit current at frequency $p$ flowing from 1–2 terminals

For $R_q$ first short-circuited.

$$i_{q1} = PK_a \tag{9}$$

$$i_{p1} = \frac{P}{Z_{ps}} \tag{10}$$

If the short circuit on $R_q$ is removed, the following two additional currents will flow due to superposition of a new voltage $-i_qR_q$

$$i_{q2} = \frac{-i_qR_q}{Z_{qs}} \tag{11}$$

and

$$i_{p2} = -i_qR_qK_b \tag{12}$$

$$i_q = i_{q1} + i_{q2} = \frac{PK_a}{1 + \dfrac{R_q}{Z_{qs}}} \tag{13}$$

$$i_p = i_{p1} + i_{p2} = \frac{P}{Z_{ps}} - \frac{PK_aK_bR_q}{1 + \dfrac{R_q}{Z_{qs}}} \tag{14}$$

The efficiency of the frequency translation, measured by the ratio of the power delivered to $R_q$ to the power into terminals 1–2, is

$$\eta = \frac{i_q{}^2R_q}{i_pP} = \frac{\left(\dfrac{K_a}{1 + \dfrac{R_q}{Z_{qs}}}\right)^2 R_q}{\dfrac{1}{Z_{ps}} - \dfrac{K_aK_bR_q}{1 + \dfrac{R_q}{Z_{qs}}}} \tag{15}$$

which is maximum for

$$R_q = \frac{Z_{qs}}{\sqrt{1 - K_aK_bZ_{ps}Z_{qs}}} \tag{16}$$

The maximum efficiency is then

$$\eta_{\max} = \frac{K_a{}^2Z_{ps}Z_{qs}}{(1 + \sqrt{1 - K_aK_bZ_{ps}Z_{qs}})^2} \tag{17}$$

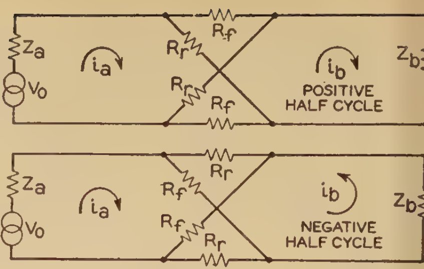

**Figure 8. Equivalent circuit of a double balanced modulator**

When equation 16 is substituted in (14 it is found that

$$R_p = \frac{P}{i_p} = \frac{Z_{ps}}{\sqrt{1 - K_aK_bZ_{ps}Z_{qs}}} \tag{18}$$

In order to evaluate $K_aK_b$, open-circuit impedance measurements must also be made. By superposition methods like those used in obtaining equations 11 and 12 it can readily be shown that

$$\frac{1}{Z_{po}} = \frac{1}{Z_{ps}} - K_aK_bZ_{qs} \tag{19}$$

$$\frac{1}{Z_{qo}} = \frac{1}{Z_{qs}} - K_aK_bZ_{ps} \tag{20}$$

From these two equations, it follows that

$$\frac{Z_{ps}}{Z_{po}} = \frac{Z_{qs}}{Z_{qo}} \tag{21}$$

$$K_aK_b = \frac{\dfrac{1}{Z_{ps}} - \dfrac{1}{Z_{po}}}{Z_{qs}} \tag{22}$$

and $K_aK_b$ can be determined from any three of the open-short measurements by using (21) and (22). It follows that

$$K_aK_bZ_{ps}Z_{qs} = 1 - \frac{Z_{ps}}{Z_{po}} \tag{23}$$

Upon substitution in (16) and (18) it is found that

$$R_q = \sqrt{Z_{qo}Z_{qs}} \tag{24}$$

and

$$R_p = \sqrt{Z_{po}Z_{ps}} \tag{25}$$

when 3–4 is terminated in $R_q$ for maximum efficiency.

Open- and short-circuit measurements enable us to compute the optimum efficiency from equation 17 only if the transfer admittance $K_a$ is known. If the reciprocal theorem holds, $K_a = K_b$ and $K_a$ can be determined from (23). The optimum efficiency is then

$$\eta_{\max} = \frac{1 - \sqrt{\dfrac{Z_{ps}}{Z_{po}}}}{1 + \sqrt{\dfrac{Z_{ps}}{Z_{po}}}} \tag{26}$$

**Table I. Correspondence Between Currents Entering and Leaving a Reversing-Switch Modulator**

| Component on One Side of Modulator | Corresponding Components on Other Side of the Modulator | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $\frac{2k^*}{\pi}$ | | $-\frac{2k}{3\pi}$ | | $\frac{2k}{5\pi}$ | | $-\frac{2k}{7\pi}$ | |
| $I_0$ | $I_{1-}$ | $I_{1+}$ | $I_{3-}$ | $I_{3+}$ | $I_{5-}$ | $I_{5+}$ | $I_{7-}$ | $I_{7+}$ |
| $I_1$ | $I_0$ | $I_{2-}$ | $I_{2+}$ | $I_{4-}$ | $I_{4+}$ | $I_{6-}$ | $I_6$ | $I_8$ |
| $I_{1+}$ | $I_0$ | $I_{2+}$ | $I_{2-}$ | $I_{4+}$ | $I_{4-}$ | $I_{6+}$ | $I_{6-}$ | $I_8$ |
| $I_{2-}$ | $I_{1-}$ | $I_{3-}$ | $I_{1+}$ | $I_{5-}$ | $I_{3+}$ | $I_{7-}$ | $I_{5+}$ | $I_9$ |
| $I_{2+}$ | $I_{1+}$ | $I_{3+}$ | $I_{1-}$ | $I_{5+}$ | $I_{3-}$ | $I_{7+}$ | $I_{5-}$ | $I_{9+}$ |
| $I_{3-}$ | $I_{2-}$ | $I_{4-}$ | $I_0$ | $I_{6-}$ | $I_{2+}$ | $I_{8-}$ | $I_{4+}$ | $I_{10-}$ |
| $I_{3+}$ | $I_{2+}$ | $I_{4+}$ | $I_0$ | $I_{6+}$ | $I_{2-}$ | $I_{8+}$ | $I_{4-}$ | $I_{10+}$ |
| $I_{4-}$ | $I_{3-}$ | $I_5$ | $I_{1-}$ | $I_{7-}$ | $I_{1+}$ | $I_{9-}$ | $I_{3+}$ | $I_{11-}$ |
| $I_{4+}$ | $I_{3+}$ | $I_{5+}$ | $I_{1+}$ | $I_{7+}$ | $I_{1-}$ | $I_{9+}$ | $I_{3-}$ | $I_{11+}$ |
| $I_{5-}$ | $I_{4-}$ | $I_{6-}$ | $I_{2-}$ | $I_{8-}$ | $I_0$ | $I_{10-}$ | $I_{2+}$ | $I_{12-}$ |
| $I_{5+}$ | $I_{4+}$ | $I_{6+}$ | $I_{2+}$ | $I_8$ | $I_0$ | $I_{10+}$ | $I_{2-}$ | $I_{12+}$ |
| $I_{6-}$ | $I_{5-}$ | $I_{7-}$ | $I_{9-}$ | $I_{8-}$ | $I_{1-}$ | $I_{11-}$ | $I_{1+}$ | $I_{13-}$ |
| $I_{6+}$ | $I_{5+}$ | $I_{7+}$ | $I_{3+}$ | $I_{9+}$ | $I_{1+}$ | $I_{11+}$ | $I_{1-}$ | $I_{13+}$ |
| $I_{7-}$ | $I_{6-}$ | $I_8$ | $I_{4-}$ | $I_{10-}$ | $I_{2-}$ | $I_{12-}$ | $I_0$ | $I_{14-}$ |
| $I_{7+}$ | $I_{6+}$ | $I_{8+}$ | $I_{4+}$ | $I_{10+}$ | $I_{2+}$ | $I_{12+}$ | $I_0$ | $I_{14+}$ |
| $I_{8-}$ | $I_{7-}$ | $I_{9-}$ | $I_{5-}$ | $I_{11-}$ | $I_{3-}$ | $I_{13-}$ | $I_{1-}$ | $I_{15-}$ |

NOTE: A current of the frequency indicated in the first column will be modulated to produce the components written on the same line, the magnitudes of which are the magnitude of the generating current multiplied by the factors at the top of the columns.

$$*k = \left(\sqrt{\frac{R_r}{R_f}} - 1\right) \Big/ \left(\sqrt{\frac{R_r}{R_f}} + 1\right)$$

**Table II. Performance of Double-Balanced Modulator (Ideal Reversing Switch) for Various Input and Output Terminations**

| Modulator Terminations |  |  |  | Modulator Impedance |  | Modulator Loss or Efficiency |  |
|---|---|---|---|---|---|---|---|
| Input Circuit |  | Output Circuit |  |  |  |  |  |
| Signal | Others | Signal | Others | Input Signal | Output Signal | Voltage Ratio | Decibels |
| $R$ | $R$ | $R$ | $R$ | $R$ | $R$ | $\frac{2}{\pi}$ | 3.9 |
| $R$ | any value | $R$ | $R$ | $R$ |  | $\frac{2}{\pi}$ | 3.9 |
| $R$ | $R$ | $R$ | 0 | $\frac{2R}{\pi^2-2}$ | $R$ | $\frac{2}{\pi}$ | 3.9 |
| $R$ | $R$ | $R$ | $\infty$ | $\frac{(\pi^2-2)R}{2}$ | $R$ | $\frac{2}{\pi}$ | 3.9 |
| $R$ | $\frac{(\pi^2-2)R}{2}$ | $\frac{(\pi^2-2)R}{2}$ | 0 | $R$ | $\frac{\pi^2(\pi^2-2)R}{6\pi^2-16}$ | $\frac{\pi}{\sqrt{2(\pi^2-2)}}$ | 2 |
| $R$ | $\frac{2R}{\pi^2-2}$ | $\frac{2R}{\pi^2-2}$ | $\infty$ | $R$ | $\frac{(6\pi^2-16)R}{\pi^2(\pi^2-2)}$ | $\frac{\pi}{\sqrt{2(\pi^2-2)}}$ | 2 |
| $R$ | 0 | $R$ | 0 | 0 | 0 |  | $\infty$ |
| $R$ | $\infty$ | $R$ | $\infty$ | $\infty$ | $\infty$ |  | $\infty$ |
| $R$ | 0 | $R$ | $\infty$ | $\frac{\pi^2 R}{4}$ | $\frac{4}{\pi^2}R$ | $\frac{4\pi}{4+\pi^2}$ | 0.85 |
| $R$ | $\infty$ | $R$ | 0 | $\frac{4}{\pi^2}R$ | $\frac{\pi^2}{4}R$ | $\frac{4\pi}{4+\pi^2}$ | 0.85 |
| $R$ | 0 | $\frac{4}{\pi^2}R$ | $\infty$ | $R$ | $\frac{4}{\pi^2}R$ | 1 | 0 |
| $R$ | $\infty$ | $\frac{\pi^2}{4}R$ | 0 | $R$ | $\frac{\pi^2}{4}R$ | 1 | 0 |
| $R_s$ | $R_s'$ | $R_r$ | $R_r'$ | $Z_i$* | $Z_0$* | $\eta$* |  |

$$*Z_i = \frac{\pi^2 R_r'(R_r + R_s') + 4(R_r - R_r')R_s'}{\pi^2(R_r + R_s') - 4(R_r - R_r')} \qquad Z_0 = \frac{\pi^2 R_s'(R_s + R_r') + 4(R_s - R_s')R_r'}{\pi^2(R_s + R_r') - 4(R_s - R_s')}$$

$$\eta = \frac{4\pi(R_r' + R_s')\sqrt{R_s R_r}}{\pi^2(R_s + R_r')(R_r + R_s') - 4(R_r - R_r')(R_s - R_s')}$$

If the input signal generator has an internal impedance, most efficient energy delivery to the modulator will, of course, result if this impedance is made equal to $R_p$.

Equivalent $T$, $\pi$, and bridge networks can obviously be drawn from the open- and short-circuit measurements as in four-terminal linear networks.

It appears that even in a plate- or grid-circuit modulator the formulas of equations 24, 25, and 26 can be applied to the plate or grid circuit, respectively, where the signals are small compared to the carrier, inasmuch as the modulating parts of these circuits are linear and bilateral with no internal energy sources.

## Double-Balanced or Reversing-Switch Modulator*

A number of interesting conclusions can be reached about copper-oxide modulators by assuming that the copper oxide acts like a switch having a low resistance value when the positive half-cycle of the carrier voltage is across the disk and a high resistance value during the negative half-cycle. The circuits of figures 2c, 2d, or 2e can then be represented by the equivalent circuit of figure 8.

The input signal generator $V_0$ is applied out of an input circuit impedance $Z_a$, and the output signal is delivered to the output circuit impedance $Z_b$. Both $Z_a$ and $Z_b$ in general will be functions of frequency.

If $Z_a = Z_b = R$ at all frequencies it can easily be shown that the circuit will operate most efficiently for

$$R = \sqrt{R_r R_f} \tag{27}$$

The signal input current will then be the only frequency in $i_a$.

$$i_a = \frac{V_0}{2R} \tag{28}$$

From the properties of lattice networks it follows, that

$$i_b = \frac{V_0}{2R}\cdot\frac{\sqrt{\frac{R_r}{R_f}} - 1}{\sqrt{\frac{R_r}{R_f}} + 1}\cdot f(t) \tag{29}$$

where

$$f(t) = \begin{cases} +1 \text{ for positive half-cycle of carrier} \\ -1 \text{ for negative half-cycle of carrier} \end{cases}$$

Letting

$$f(t) = \frac{4}{\pi}\left(\cos ct - \frac{1}{3}\cos 3\,ct + \frac{1}{5}\cos 5\,ct\ldots\right)$$

and

$$k = \frac{\sqrt{\frac{R_r}{R_f}} - 1}{\sqrt{\frac{R_r}{R_f}} + 1} \tag{30}$$

$$i_b = \frac{V_0 k}{2R}\cdot\frac{4}{\pi}\left[\cos ct - \frac{1}{3}\cos 3ct + \frac{1}{5}\cos 5ct\ldots\right] \tag{31}$$

The magnitude of the single-sideband output current is

$$i_{1+} = i_{1-} = \frac{2k}{\pi}\cdot\frac{V_0}{2R} \tag{32}$$

and the efficiency

$$\eta = \frac{4}{\pi^2}k^2 \tag{33}$$

In addition currents flow in the output circuit at both sidebands of all odd harmonics of the carrier frequency. These can be represented by $i_{3+}$, $i_{3-}$, $i_{5+}$, etc. No currents flow at the sideband frequencies of the even harmonics of the carrier, $i_{2+}$, $i_{2-}$, . . .

If $V_0$ should be replaced by an equal amplitude generator at any of the sideband frequencies, $V_{1+}$, $V_{2-}$, etc., then the input current would in any case be

$$i_{1+} = \frac{V_{1+}}{2R},\; I_{2-} = \frac{V_{2-}}{2R}, \text{ etc.}$$

The correspondence between the magnitudes of these entering currents and the magnitudes of the output currents at the modulation product frequencies are shown in table I. Reciprocal relations between the driving voltage at one frequency and the output current at another frequency are obvious.

## Generalized Reflection Theory

Superposition permits us to apply simultaneously driving forces of the frequencies tabulated above in any relative phases and amplitudes that we care to choose on either side of the modulator. If simultaneously $I_0$ is applied on one side of the modulator and

$$(I_{1+})\,\frac{2k}{\pi}\cdot\frac{Z_{1+} - R}{Z_{1+} + R}$$

is applied to the other set of modulator terminals, then the total current at the output terminals at the sideband frequency (1+) will be

$$(I_{1+})\,\frac{2k}{\pi}\cdot\left[1 - \frac{Z_{1+} - R}{Z_{1+} + R}\right] \tag{34}$$

This is equivalent to saying that a resistance $R$ at the sideband frequency (1+)

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* Referred to in the German literature as the "ring modulator."

# The Magnesium-Copper Sulphide Rectifier Battery Charger for Railroad Passenger Cars

By C. A. KOTTERMAN
NONMEMBER AIEE

**Synopsis:** When the railroads began air conditioning their trains, adequate charging of the storage batteries associated with air-conditioning systems became an important factor in the new development. The capacity of the axle driven d-c generator charger was increased; however, supplementary charging was frequently necessary or desirable, particularly when the axle generators were not operating. The railroads met this problem by using portable motor generator sets, wiring their stations and yards with standby service and through the use of small, compact, dry-disk rectifier battery chargers of sufficient current capacities to charge one or two car batteries simultaneously. The first rectifier developed for this service made use of the magnesium-copper sulphide dry-disk type. The mechanism of this rectifier is here briefly discussed, design features enumerated, and the type of rectifier battery chargers developed for railroad use described.

STORAGE BATTERIES were first added to railroad passenger and Pullman coaches about 40 years ago to provide power for electric lights which replaced the gas and oil lamps. These batteries were charged by means of axle-driven d-c generators. Electric ventilating fans were added later but under normal operating conditions the generators adequately charged the batteries. With the advent, however, of electromechanical air-conditioning equipment on railroad cars demanding d-c currents varying from 150 to nearly 300 amperes, an entirely new concept of storage-battery equipment and charging had to be worked out. In a few short years the battery load has increased from 25 to 50 amperes to nearly 300 amperes per car on some of the present-day streamlined completely air-conditioned trains. The combined efforts of storage-battery, air-conditioning, and rolling-stock engineers have accomplished a truly remarkable result in providing high-intensity indirect illumination together with air conditioning on modern trains.

This improvement in the traveling public's comfort and convenience has created many difficult problems which had to be solved. Among them may be mentioned the development of a 1,000-ampere-hour-capacity storage battery small enough in size and weight to be mounted on a coach. Adequate charging facilities had to be developed to meet the increased loads on batteries. All of this has become a reality without increasing the size of the trucks or other parts of the cars. Under normal train operating conditions, the axle-driven generator operates enough of the time to charge the batteries adequately. During the summer months, however, when the air-conditioning equipment is used to the limit to meet hot-weather conditions, supplementary or so-called "yard" charging often becomes necessary. Also, in bad winter weather when snow and ice affect the axle drive and the battery ampere-hour capacity is lowered, supplementary charging is also required.

The railroads have handled this situation in several ways. Some coach yards and stations have been equipped with d-c charging lines supplied by one or more motor generator sets. This is a costly system to install, requiring quite an investment in copper feeder cables to handle the large charging currents necessary without introducing too much *IR* drop in the charging lines.

Portable or mobile motor generator sets usually of sufficient capacity to charge the batteries on two cars simultaneously are also used. They meet the need for supplementary charging equipment but their weight and lack of easy maneuverability often restrict their use in badly congested coach yards, particularly in the winter with snow and ice hampering their movement.

Some railroads have installed 220-volt 60-cycle three-phase systems for standby service in their yards and stations. Many of the air-conditioning systems on trains include a 10–20-horsepower three-phase motor for driving the compressor associated with the air-conditioning equipment on a standing car. This is extra weight that has to be carried with the car for the sole purpose of providing standby service. The 220-volt a-c supply is, however, readily available for battery charging purposes and at a reasonable cost.

About two years ago, when the charging problem was fully realized, the P. R.

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has been connected to the output terminals of the modulator and in this resistance is an internal zero-impedance generator of voltage

$$2R(I_{1+})\,\frac{2k}{\pi}\cdot\frac{Z_{1+}-R}{Z_{1+}+R} \qquad (35)$$

This resistance $R$ at sideband frequency $(1+)$ must be infinite at all other frequencies, if in parallel we assume another resistance of $R$ at all frequencies except $(1+)$ at which it is infinite.

The equivalent impedance at frequency $(1+)$ at the modulator terminals connected to the $(1+)$ resistance with its internal generator, is the ratio of $(1+)$ voltage to $(1+)$ current.

$$Z=\frac{\frac{2k}{\pi}I_{1+}\cdot 2R-\frac{2k}{\pi}\cdot I_{1+}\cdot\left[1-\frac{Z_{1+}-R}{Z_{1+}+R}\right]R}{\frac{2k}{\pi}I_{1+}\cdot\left[1-\frac{Z_{1+}-R}{Z_{1+}+R}\right]} \qquad (36)$$

which reduces to

$$Z=Z_{1+} \qquad (37)$$

$Z_{1+}$ may be real or complex as it involves only the amplitude and phase of the superimposed voltage of upper-sideband frequency. It can readily be seen then that the solution for current flow at this frequency of equation 34 is identical with the case of linear networks in which the current is expressed as that flowing in a matched circuit modified by a reflection factor. Reflection from any modulation-product frequency can be similarly treated.

A number of cases have been worked out of efficiencies and impedances in such modulators for transmission between an input signal and a single-sideband output signal. The modulating element has been assumed perfect ($k$ = 1) and the terminations pure resistances. The results are shown in table II.

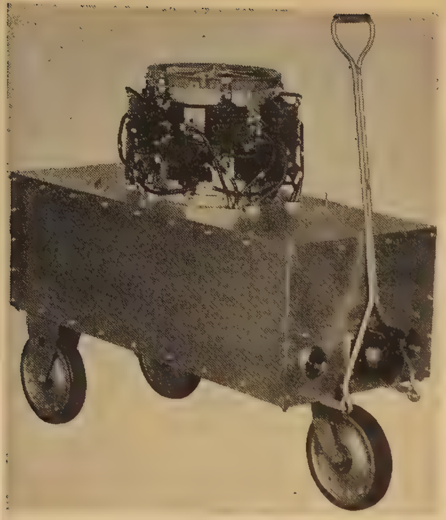


**Figure 1. Mobile charger with louvred weatherproof cover removed**

Mallory and Company, Inc., working in close co-operation with engineers of several railroads, evolved a heavy-duty dry-disk type of rectifier for converting three-phase 60-cycle current to direct current of sufficient current output to handle the air-conditioning load on a standing car or to charge one or two car batteries simultaneously. The current capacity of this rectifying unit together with the small physical size and weight of the charger made possible a practical battery charger easy to wheel around with operation fully automatic and reasonably foolproof. Weighing but 600 pounds with a width of 20 inches, capable of delivering 200 amperes into a 16-cell battery or 100 amperes into a 32-cell battery, this charger can be manipulated in the narrow space between cars in coach yards.

The rectifying element used in these battery chargers is of the contact type employing a magnesium-copper sulphide junction, the invention of Samuel Ruben. Such a rectifier consists essentially of a conductor and semiconductor in more intimate contact than physical juxtaposition and pressure can give.

There are three widely known types of contact rectifiers, namely, the copper-copper oxide, the iron-selenium, and the magnesium-copper sulphide rectifiers. During recent years both the copper-copper oxide and the magnesium-copper sulphide types have been developed to the point where they are capable of handling large currents per unit area. The iron-selenium rectifier has never been considered seriously as a heavy-duty type.

The copper-copper oxide rectifier of the sprayed-plate type has a current capacity of approximately 1.2 amperes per square inch of rectifying area when properly ventilated, the plate junction serving also as its own radiator to provide sufficient cooling area to dissipate heat generated during operation.

The magnesium-copper sulphide rectifying junction has a current capacity of approximately 60 amperes per square inch when properly ventilated. Due to the high current density at which the magnesium-copper sulphide rectifier can be worked, it is possible to build such a rectifier for large d-c outputs in a very small physical size. As a matter of fact, the type illustrated in figure 1 is but 18 inches in diameter by 12 inches high, weighs 100 pounds including ventilating system, and delivers 10 kw. These figures, of course, do not include the three-phase transformer.

Before describing the various types of rectifier battery chargers which have been developed for the railroad application, it is desirable to consider a-c circuit systems in connection with rectifiers for battery charging. Rectified voltages are frequently less than the a-c line voltages, therefore it is necessary to use some form of step-down transformer to reduce the line voltage to a suitable input value to the rectifier. The use of a transformer introduces transformer design and suitable transformer-rectifier circuits into the rectifier picture. The very simplest trans-

**Figure 2. Transformer-rectifier circuits**

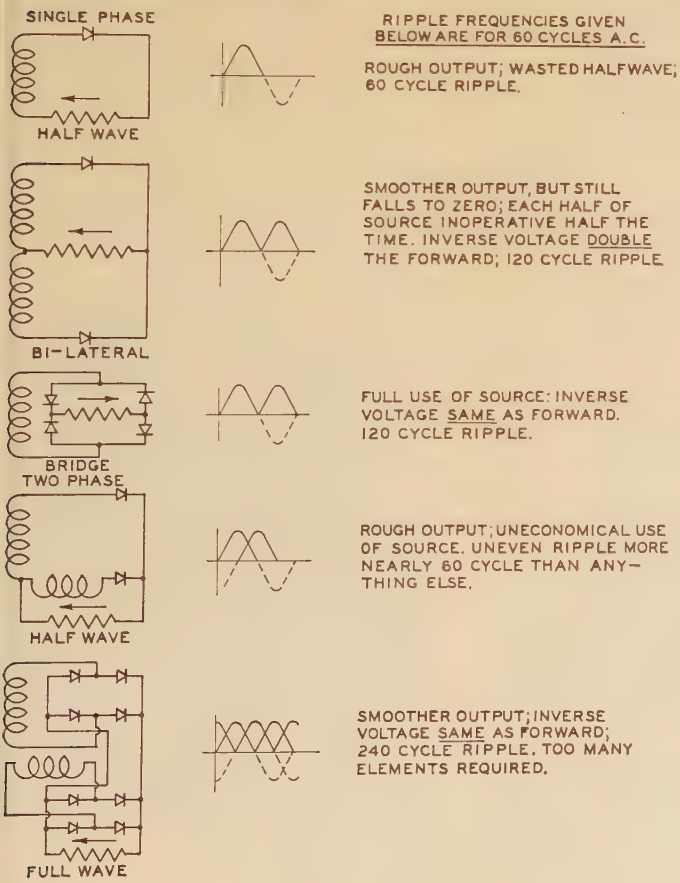
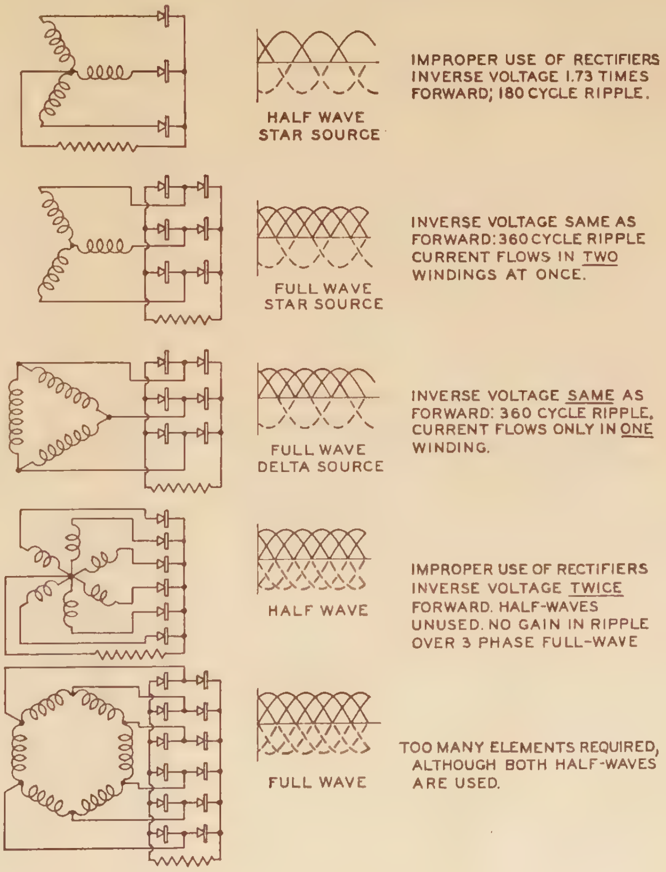

SINGLE PHASE
HALF WAVE
RIPPLE FREQUENCIES GIVEN BELOW ARE FOR 60 CYCLES A.C.
ROUGH OUTPUT; WASTED HALF WAVE; 60 CYCLE RIPPLE.
BI-LATERAL
SMOOTHER OUTPUT, BUT STILL FALLS TO ZERO; EACH HALF OF SOURCE INOPERATIVE HALF THE TIME. INVERSE VOLTAGE DOUBLE THE FORWARD; 120 CYCLE RIPPLE.
BRIDGE
FULL USE OF SOURCE: INVERSE VOLTAGE SAME AS FORWARD. 120 CYCLE RIPPLE.
TWO PHASE
HALF WAVE
ROUGH OUTPUT; UNECONOMICAL USE OF SOURCE. UNEVEN RIPPLE MORE NEARLY 60 CYCLE THAN ANYTHING ELSE.
FULL WAVE
SMOOTHER OUTPUT; INVERSE VOLTAGE SAME AS FORWARD; 240 CYCLE RIPPLE. TOO MANY ELEMENTS REQUIRED.

**Figure 3. Transformer-rectifier circuits**


HALF WAVE STAR SOURCE
IMPROPER USE OF RECTIFIERS INVERSE VOLTAGE 1.73 TIMES FORWARD; 180 CYCLE RIPPLE.
FULL WAVE STAR SOURCE
INVERSE VOLTAGE SAME AS FORWARD: 360 CYCLE RIPPLE CURRENT FLOWS IN TWO WINDINGS AT ONCE.
FULL WAVE DELTA SOURCE
INVERSE VOLTAGE SAME AS FORWARD: 360 CYCLE RIPPLE. CURRENT FLOWS ONLY IN ONE WINDING.
HALF WAVE
IMPROPER USE OF RECTIFIERS INVERSE VOLTAGE TWICE FORWARD. HALF-WAVES UNUSED. NO GAIN IN RIPPLE OVER 3 PHASE FULL-WAVE
FULL WAVE
TOO MANY ELEMENTS REQUIRED, ALTHOUGH BOTH HALF-WAVES ARE USED.

former-rectifier circuit known is illustrated in figure 2. This is a half-wave single-phase circuit producing a very rough d-c output with an inoperative half-wave resulting in a 60-cycle ripple. A somewhat better circuit is the bilateral where the d-c output is smoother but the direct current falls to zero. Each half of the a-c source is inoperative half the time. The inverse voltage per individual rectifier junction is double the forward voltage; however, this circuit has the advantage of a 120-cycle ripple. Probably the most efficient and satisfactory circuit for single-phase operation of rectifiers is the full-wave bridge. This circuit makes full use of the a-c source; the inverse voltage is the same as the forward voltage and the ripple is 120 cycles.

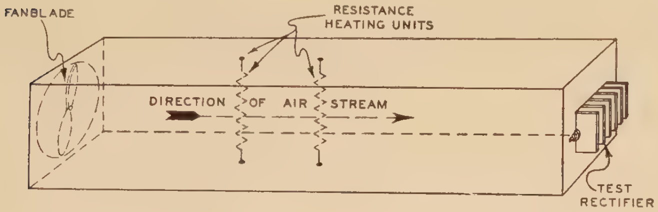


Figure 4. Wind tunnel

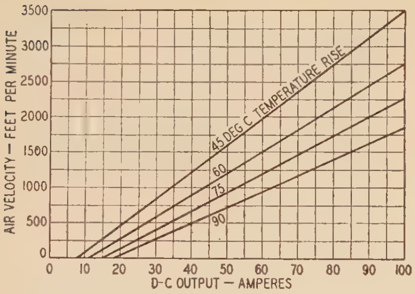


Figure 5. Air velocity versus load curves for the magnesium-copper sulphide rectifier

Three-phase full-wave

The simplest polyphase circuit is the two-phase half-wave resulting in rough d-c output, uneconomical use of the a-c source, inverse voltage the same as the forward voltage, and has a 240-cycle ripple. The chief objection to this circuit is that the circuit requires too many rectifying elements for the required d-c output.

The three-phase half-wave circuit (figure 3) makes improper use of the rectifier. The inverse voltage is 1.73 times the forward voltage. The d-c output has a 180-cycle ripple. The three-phase full-wave bridge, either star or delta connected, offers the most efficient circuit arrangement for rectifiers. Where the a-c source is star connected, the inverse voltage is the same as the forward but the current flows in two windings simultaneously. The d-c output has a 360-cycle ripple, a desirable feature if the output has to be filtered. The delta connection of the a-c source has the advantage that current flows only in one winding during a rectifying cycle. The inverse voltage is the same as the forward and the d-c output carries a 360-cycle ripple. The last-mentioned circuit arrangement has been adopted on all our heavy-duty rectifiers operating from three-phase sources.

In designing a rectifier for heavy-current battery charging two essential rectifier fundamentals are of considerable importance. One is voltage ratio, defined as the ratio of direct voltage output to alternating voltage input. Maximum voltage ratio is a function of how much alternating voltage one rectifying junction can have impressed across the junction without breaking down the insulating film between the elements of the junction. The other is the current ratio, defined as the d-c output to a-c input. Maximum current ratio is a function of the maximum safe current density at which the rectifying junction can be operated with stability. Knowing the transformer-rectifier circuit system together with the voltage and current ratios, one can design a rectifier for battery charging to meet any charging conditions. As the charging rate is a function of the battery electromotive force, the chief requisite is to design the system so that the direct voltage of the rectifier will not fall below the battery electromotive force during any portion of the rectifier conducting cycle. When this condition is fulfilled, the design simplifies itself to the proper application of the voltage and current ratios of the sulphide rectifier in conjunction with the battery electromotive force.

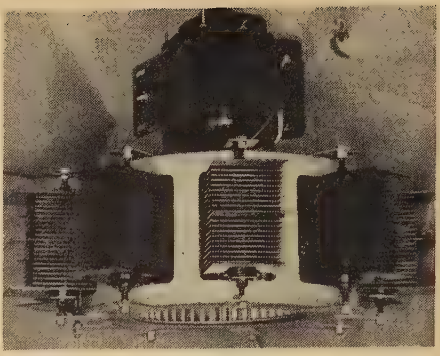


Figure 6. Drum housing with centrifugal-blower wheel

All contact rectifiers are essentially resistance devices, therefore they generate heat when rectifying. The life expectancy of such rectifiers is based mainly on their operating temperature. In the case of the magnesium-copper sulphide rectifier, the optimum temperature is 90 degrees centigrade or 190 degrees Fahrenheit. So long as this temperature is not exceeded, during normal operating conditions, the life of the copper sulphide rectifier will be unaffected. Abnormal operating temperatures exceeding the above values appreciably will have some affect on life. As a matter of interest, we have conducted a life test, in excess of 5,000 hours, on a magnesium-copper sulphide rectifier of the type used in our railroad battery chargers, at operating temperatures averaging 130 degrees centigrade or 266 degrees Fahrenheit with little effect on the life of the rectifier. The lower the operating temperature, the longer the life when other operating conditions are normal. Heat generated at the rectifying junction must therefore be removed faster than by simple convection cooling if the rectifier is to deliver large direct currents. The magnesium-copper sulphide rectifier of 1.7 square inches of rectifying area with 3.5 inches square radiator plates or cooling fins will handle 100 amperes direct current safely when placed in a stream of air having a velocity of approximately 2,000 feet per minute. This current density is based on three-phase full-wave operation.

A thorough study of rectifier ventilation was made by the use of a wind tunnel. The tunnel consisted of a box 18 inches square in cross section and ten feet long (figure 4). One end was closed except for an opening or window in the

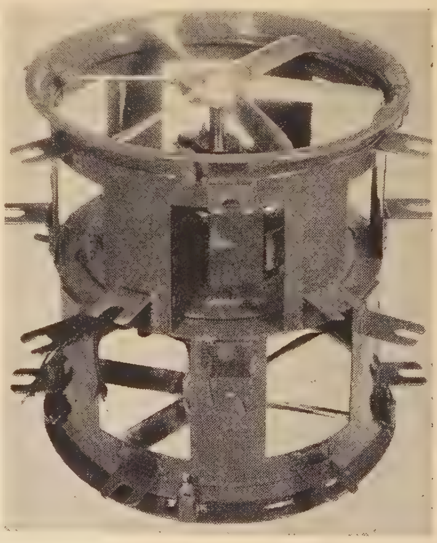


Figure 7. Propeller-blade power dome

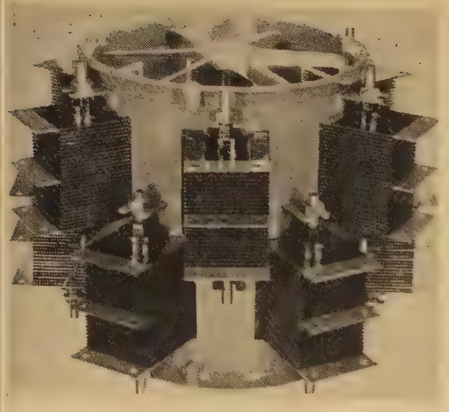


Figure 8. Propeller-blade power dome with rectifiers

center into which the test rectifier was set. The other end of the box was attached to a blower system capable of providing air velocities as high as 5,000 feet per minute. Electric heating elements were placed midway between the ends inside the box to raise the temperature of the air stream for the purpose of studying the behavior of the test rectifiers at elevated temperatures. The compiled data from the wind-tunnel tests enables us to design a ventilating system for any rectifier-transformer combination and to predict within engineering limitations the operating temperature of a power rectifier for any given ambient temperature. Figure 5 is a family of curves, air velocity versus load as obtained by the wind-tunnel tests.

To increase the current-handling capacity of the magnesium-copper sulphide rectifier forced cooling has been developed which led to the study of accelerated air flow through rectifiers. After trying various methods, one was finally evolved of supporting the rectifier elements in the wall of a hollow drum structure, mounting a pressure-type centrifugal blower wheel inside the drum. Figure 6 shows one of the earlier models employing this construction. Air is drawn in through the opening in the center of the fan rotor, then discharged tangentially from the blades through the rectifiers. This permits a very compact construction together with efficient cooling.

The rectifiers are placed symmetrically around the fan-wheel housing. This construction lends itself to very simplified wiring of the rectifiers. The whole structure is known as the "d-c power dome." It is usually supported on top of another housing in which the power transformer is placed. The air discharged through the ventilating fins of the rectifier is first drawn through and around the coils of the transformer, therefore giving the transformer forced cooling. In this way smaller and lighter-weight transformers may be employed.

The centrifugal-type fan wheel is essentially a pressure blower. It delivers large volumes of air with comparatively low velocities. Where the rectifier cooling fins are close together in order to make as compact assembly as possible, high velocity through the fins is desirable. A fan which would deliver high air velocity rather than great volumes of air was desired and this was developed in conjunction with manufacturers of propeller-type fan blades. The method of employing this type fan is shown in figure 7.

A one-third-horsepower motor is supported inside the drum cage. The motor shaft has a double extension so that two fans, one right hand and one left hand, may be rotated simultaneously. Air is drawn in by both propellers building up a pressure inside the drum which is discharged out through the rectifiers mounted in openings in the drum (figure 8).

In the two cooling methods just described, the rectifiers are mounted around a drum or cage. A modification of this principle is employed in a very recent development of forced-cooled rectifiers for large power outputs. In this design the rectifiers are mounted radially in a plane around the motor which drives a single fan. It develops an air pressure inside the housing, forcing the air out through the rectifiers (figure 9).

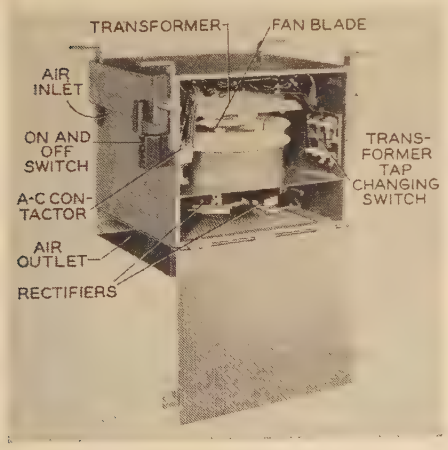


Figure 9. Undercar charger

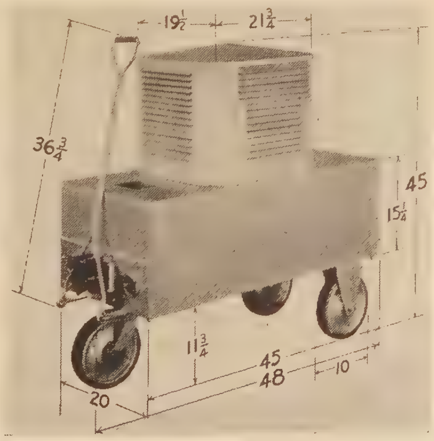


Figure 10. Mobile charger

The railroad battery chargers have been developed in two forms—the "mobile" charger for platform or yard charging and the "on-a-car" type for mounting on and traveling with a car. Both types consist essentially of a three-phase power transformer, three-phase full-wave bridge rectifiers with ventilating system, a chassis or mounting device and housing together with provision for altering the charging rate and compensating for line-voltage variations. Protective circuits are also incorporated.

The mobile charger with principal dimensions shown in figure 10 is manufactured in two types. In one form the charging rate is varied by means of primary taps on the three-phase power transformer (see figure 11). In other models a self-regulating transformer is employed. In this type a sensitive voltage relay across the d-c output of the rectifier maintains a constant d-c output by automatically adjusting the turns ratio of the transformer to compensate for line-voltage variations (figure 14). Figure 12 is a typical charging curve obtained with a charger equipped with a manual control. Figure 13 is a charging curve using the type having the self-regulating transformer.

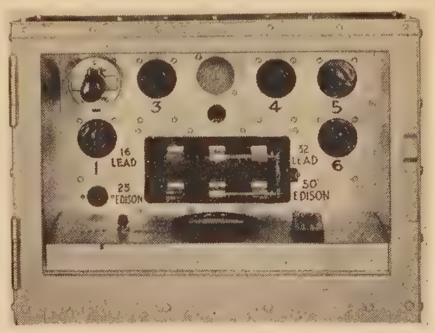


Figure 11. Mobile-charger control panel showing "wander" plug and tap-changing receptacles

As the life of the rectifying units depends considerably on proper and continuous ventilation, it is essential that the motor associated with the ventilating system be interlocked with the hold-in coil of the main magnetic contactor or be provided with an individual contactor with overload protection interlocked with the main contactor. A single-phase 220-volt motor is employed so that phase reversal will not affect the direction of rotation as the fans must rotate in one direction only. The "on and off" switch which starts and stops a charge is also in the fan circuit. It is provided with a thermal overload so in case of fan motor failure, the a-c power to the transformer will be disconnected.

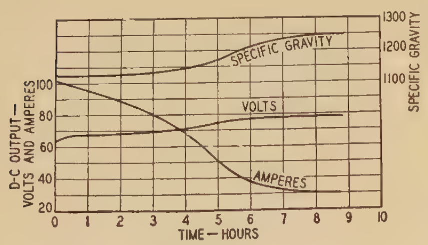


**Figure 12. Typical charging curve from manually operated mobile charger**

For 600-ampere-hour lead battery

The charging rate on the manually controlled model is varied by means of a "wander" plug and six primary tap receptacles as shown in figure 11. It, however, does not compensate automatically for line-voltage variations. This simple method provides a wide range of charging rates from a few amperes to the full output of the machine and has proved quite adequate for battery charging. Field experience has shown that about 90 per cent of the use of these chargers is to pump as many ampere-hours into a battery as possible in a short time, or to carry the air compressor load of a standing car with the battery floating across the rectifier. Rarely have these periods exceeded three hours.

The charging rate on the automatic regulating type is set by turning a control knob located on the control panel. The charging rate will remain constant until the electromotive force of the battery has risen to a value which can no longer be compensated for by the self-regulating feature at which time the charge will start tapering abruptly, a highly desirable feature in storage-battery charging. The self-regulating feature also maintains a constant charge during line-voltage variation of plus or minus $7^1/_2$ per cent for any rough setting of the three primary line-voltage taps. These rough settings together with the plus or minus $7^1/_2$ per cent regulation provide constant output from 193-volt lines to 253-volt lines.

The fully automatic type also incorporates a current-limiting control which changes the turns ratio of the transformer should the charging rate inadvertently be increased beyond the setting for maximum safe continuous operation.

The rectifiers are wired up in two banks (figure 15), each consisting of two full-wave three-phase bridges in series, providing approximately 37–49 volts d-c output each. A double-pole double-throw switch conveniently mounted enables the two banks to be connected in parallel to provide 37–49 volts at 200 amperes to charge one or more 16-cell lead batteries or 25 cells of Edison batteries, or they may be connected in series to charge a 32-cell lead or 50-cell Edison battery at 100 amperes. Two standard d-c charging receptacles mounted at one end of the charger are connected in parallel so that two batteries may be charged simultaneously. An ammeter shunt is connected into the circuit of each charging receptacle. An ammeter, common to both circuits, indicates the charging current in either charging line. It is practical to charge a 16-cell lead and a 25-cell Edison battery simultaneously if a small series resistor is added to the lead battery charging line.

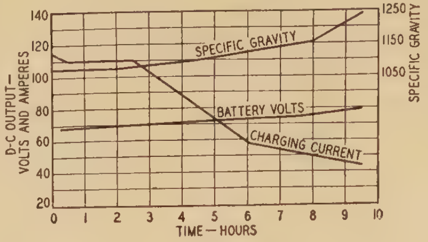


**Figure 13. Typical charging curve from self-regulating mobile charger**

For 600-ampere-hour lead battery

Both types are equipped with standard railroad three-phase four-wire a-c receptacles, the fourth conductor serving as a ground.

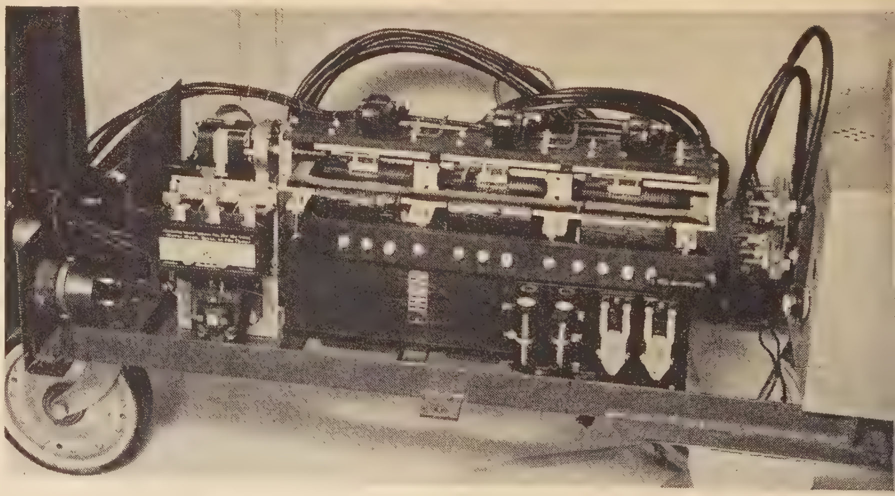


**Figure 14. Self-regulating three-phase powe transformer**

The machines are readily wheeled around on ten-inch diameter, two-inch tread rubber-tired antifriction wheels. As already stated, weighing but 600 pounds and but 20 inches wide, the possess a maximum of maneuverability.

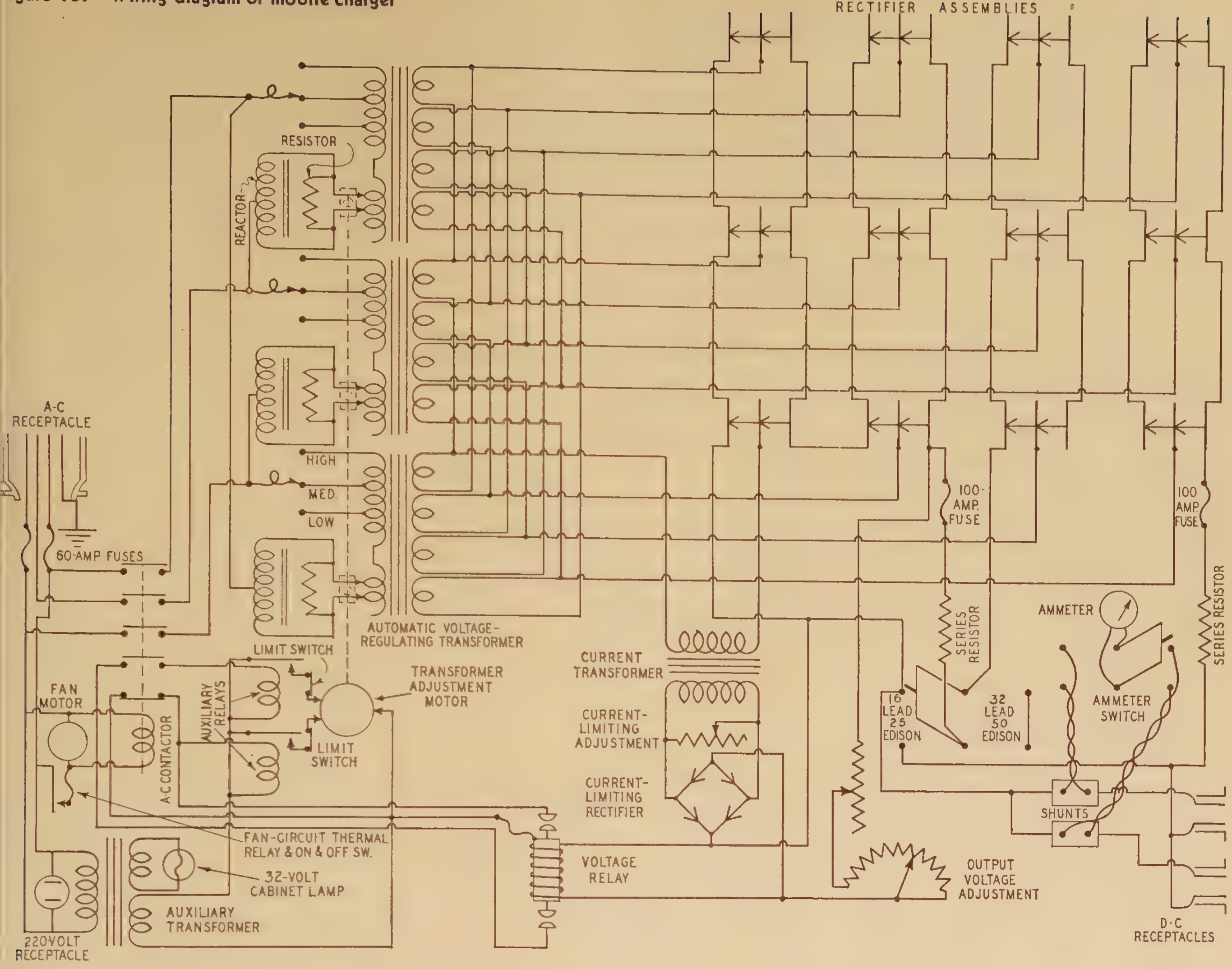
The equipment is fully protected i louvered steel housings and may b operated safely and satisfactorily in an kind of weather.

The "on-a-car" type has been developed in two forms. One shown i figure 16 is intended to be mounted i the clerestory. The other illustrate in figure 9 is enclosed in a ventilate weather-, ballast-, and cinder-proo welded steel housing for mounting underneath the car. Both forms have the sam type transformers and rectifiers togethe with the control and protective feature of the mobile types, but because they ar designed to charge a particular battery they do not need to have the flexibilit of charging rate of the mobile type. Th clerestory form, in operation on severa railroads, supplies 100 amperes into 16-cell lead or 25-cell Edison battery an 80 amperes into a 32-cell lead or 50-cel Edison battery and weighs approximatel 290 pounds. Larger-capacity chargers u to 200 amperes into 16-cell lead or 25-cel Edison or 100 amperes into 32-cell lea or 50-cell Edison can be built of smal enough size and weight to be mounted i the clerestory if desired.

The undercar type, due to its weatherproof housing, weighs more than the clerestory model but the over-all dimension are practically the same.

Manual control of the "on-a-car" typ battery charger is not needed as the regulation of the transformer-rectifier combination automatically takes care of th charging rate depending upon the specifi gravity of the battery. However, wher it is necessary or desirable automaticall

Figure 15. Wiring diagram of mobile charger



to adjust for line-voltage variation, a self-regulating transformer can be included in the equipment.

Both types operate directly from the 220-volt three-phase standby supply. They require no attention other than connecting or disconnecting this supply. One model is provided with an automatic tapering feature which reduces the charging rate to a mere trickle charge when the voltage of the battery has reached a predetermined value. Should this charger be left on inadvertently for a longer period of time than necessary to complete a normal charging cycle, the trickle rate will automatically come into operation thus preventing undue gassing of the battery.

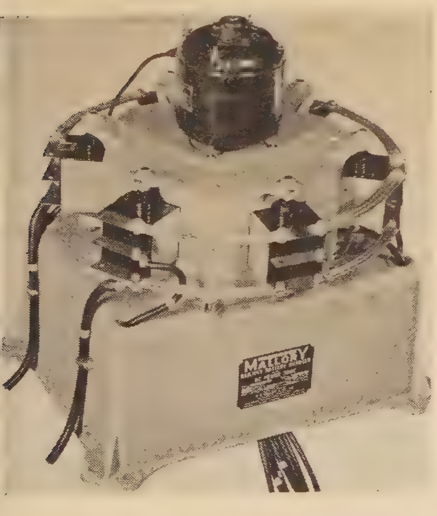


Figure 16. "On-a-car" charger

Although none has been built as yet for this service, designs are ready for an undercar type that will carry the compressor load of a stationary car. This model would eliminate the a-c standby motor and would provide auxiliary charging whenever required.

Rectifier battery chargers possess certain operating features not found in other types. They are light in weight, handle easily, and are compact enough to be used in crowded coach yards. As no heavy rotating parts are employed, they are exceedingly quiet in operation. Maintenance is reduced to a minimum as there are no commutating devices or brush wear. A very desirable feature is that the rectifier battery chargers start on load with a starting current approximately the same as the running current. This enables them to be operated directly off the 220-volt three-phase standby service.

The possibility of polarity reversal is eliminated. This feature together with the fact that the reverse current from the battery through the rectifier is of the order of an ampere, eliminates the need of reverse-current relays.

The magnesium-copper sulphide rectifier battery charger has an over-all efficiency of approximately 50 per cent. The efficiency curve is practically flat from 25 per cent full load to 125 per cent full load. The efficiency of the rectifier itself is about 55 per cent and remains at this value throughout the life of the rectifier. Very recent developments indicate that a higher efficiency may be expected of the copper-sulphide rectifier in the near future, together with greater stability of operation and even longer life than the present type.

# Pennsylvania Railroad New York-Washington-Harrisburg Electrification—Relay Protection of Power Supply System

By E. L. HARDER
ASSOCIATE AIEE

THE completion and placing into service of the Pennsylvania Railroad electrification marks the satisfactory conclusion of a relay design and application problem involving considerable pioneering work in this field. The protection problem is the provision of a system of protective relays, which in event of trouble, will automatically open circuit breakers to isolate the faulty section from the remainder of the power system. Outstanding features of the protective system are:

1. The provision of a relaying system for high-voltage lines operated with very few high-voltage breakers and with large numbers of taps, involving the opening of as many as 30 low-voltage breakers for the isolation of a single fault.

2. High-speed trolley relays, inaugurating the use of what are today known as "high-speed relays" in a-c power systems. These relays and the associated circuit breakers are not only extremely fast, clearing faults in 0.04 second total for relays and breaker, but the relays are also very selective, clearing fault currents less than maximum loads and effecting simultaneous operation over 90 per cent of the section length. High-speed a-c circuit breakers, high-speed "distance measuring" relays, transient shunts, and the load presetter, are all new developments associated with this electrification.

3. Use of locomotives and multiple-unit cars not having any main circuit breaker. Trolley circuit breakers at substations open for major faults on the moving equipment. Locomotive and substation relays are so co-ordinated as to disconnect automatically faulty equipment after the substation breakers have opened.

This paper outlines the general arrangement of the power supply system from a protective point of view, and describes the system of relays developed to provide complete protection from the generators to the motive power units. It discusses several of the more important relay problems which it was necessary to solve in connection with the electrification.

## Power Supply System

The comprehensive extent of the power supply system may readily be visualized by reference to figure 1 which shows the electrified tracks together with the location of the power sources and step-up transformer stations, the step-down transformer substations, and principal switching stations.

A typical portion of the power system is shown in figure 2. Altogether 25-cycle power is available at seven locations, either by steam or hydro generation, or in most cases by frequency conversion from 60-cycle power systems in the area served. This 25-cycle power is transmitted over nearly 1,100 miles of 132-kv single-phase lines throughout the 674 route miles of electrified territory. It is distributed at 11 kv over 2,189 miles of trolley from 61 transformer substations, the majority of which are located 6 to 12 miles apart.

The absence of 132-kv breakers at step-up and step-down transformer stations is a notable feature. Each transmission-line section with its connected step-up and step-down transformers is cleared as a unit by the low-voltage breakers in event of fault.

The transmission lines are "looped in" to the 25-cycle generating busses through the step-up transformers. This gives rise to the designation "looped-in" system in distinction to a system in which high-voltage lines are continuous past generating stations. While the "looped-in" system was adopted primarily on account of circuit breaker capacity and to limit telephone interference, it has also been found much better adapted to protection by relays. High-voltage lines are provided in balanced pairs, there being four lines from New York to Philadelphia and two elsewhere as far as protection is concerned. Physically both of the lines do not follow all of the trackage, although each station has at least two possible sources of feed. The general arrangement of a step-down transformer station is indicated in figure 3.

## The Over-All Relay Problem

From the standpoint of system protection the elements of the system to be protected are:

1. Generators.
2. Generator busses.
3. Step-up transformers.
4. Transmission lines.
    - (*a*) Line-to-line faults.
    - (*b*) Line-to-ground faults.
5. Step-down transformers.
6. Low-voltage or trolley busses.
7. Trolleys.
8. Motive power units.

In addition to protection of specific apparatus, relays are also used for effecting the desired sectionalizing under abnormal operating conditions such as out-of-synchronism and low voltage. In the terminal areas, at New York and Washington, 12-kv cables are used instead of the high-voltage lines, introducing an additional element to be protected. Special protection is also used on the 132-kv cables through Baltimore.

It is evident that the protection of the various elements enumerated must be accomplished with careful consideration of the co-ordination with the protection of other elements so that only the faulty section will be disconnected. The more important of these co-ordination problems will be discussed in the subsequent paragraphs.

## A-C Network Calculator

System voltages and currents under fault and load conditions form the fundamental basis for the relay application and the determination of these necessary data is a major problem. For the earlier stages of the electrification many of these data were obtained analytically. However, for the relaying of the complicated system involved in the through electrification, these data were obtained on the a-c network calculator developed by the Westinghouse company and owned and operated by the railroad (figure 4).

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The suggestions and recommendations of Mr. Griffith, electrical engineer of the Pennsylvania Railroad, and his associates, in the development of this over-all protective system are gratefully acknowledged. Also his helpful assistance in the preparation of this paper. The co-operation of Mr. Watkins and his associates in the consulting firm of Gibbs and Hill are likewise gratefully acknowledged. As stated in the text, the relaying of this system was largely a joint effort of the Pennsylvania Railroad, General Electric Company, and Westinghouse. Only that portion for which the Westinghouse company supplied all or part of the equipment is described.

## Generators

In addition to the conventional differential protection, generators are equipped in most cases with induction-type overcurrent relays having time and current selectivity with overcurrent relays used on the transmission lines. An additional machine protective feature is used on some of the frequency changers to prevent building up resonant torsional stresses when slipping poles. This device counts power reversals at high current, and trips for a fixed number occurring within a definite time.[1]

## High-Voltage Lines; Line-to-Line Faults

### Application Factors

The transmission lines are operated normally balanced and protected by differential current relays at the step-up transformer stations and by sensitive reverse-power relays at step-down stations, as shown in figure 2. The application differs from the normal application of balanced line relays in the following respects. First, the lines are tapped at numerous points between the two ends, where the balance protection is applied and while the unbalanced loading is minimized by operating regulations, provision must be made for normal amounts of unbalance occurring in operation and maintenance. The sectionalizing breakers intervening between generating stations are arranged for simultaneous operation, except for ground faults, to prevent unbalances from this source. Unbalances are created under load conditions by removal of sections of transmission lines between generating stations for servicing and by the removal of step-up and step-down transformers. Thus, the differential current relays are necessarily of a calibrated type which can be set intermediate between unbalance occurring under load conditions and those which will occur under fault conditions.

### Balance Line Relays

Figure 5 indicates graphically the required "trip" and "not trip" values for the balance line relays at one location and shows the superiority of the *CD* relay characteristic adopted for this application over percentage differential or straight magnitude differential relays which were also considered. Arrows indicate the progression of relaying quantities at the step-up transformer station as other breakers clear from the faulty line.

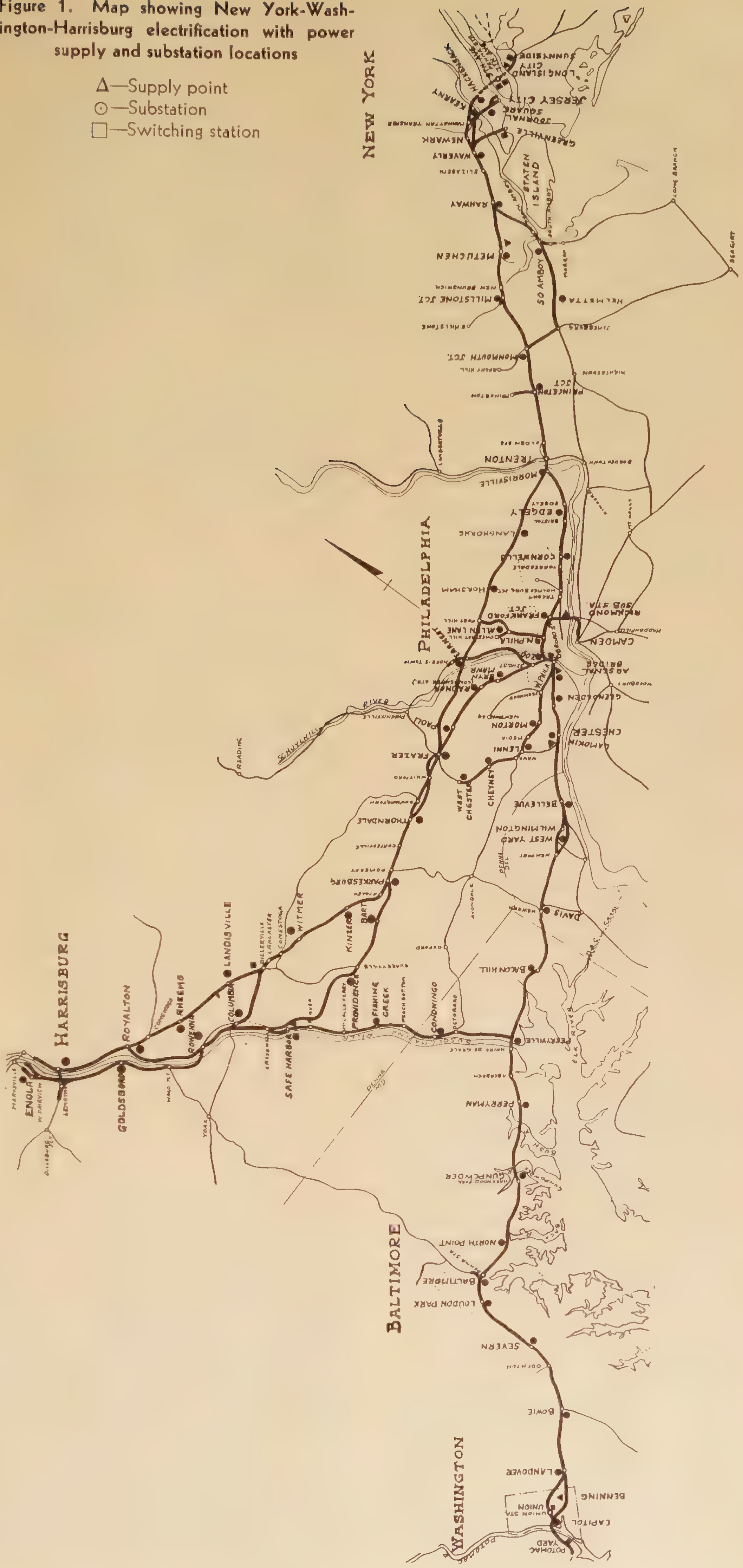

Figure 1. Map showing New York-Washington-Harrisburg electrification with power supply and substation locations

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[1] For numbered reference, see end of paper.

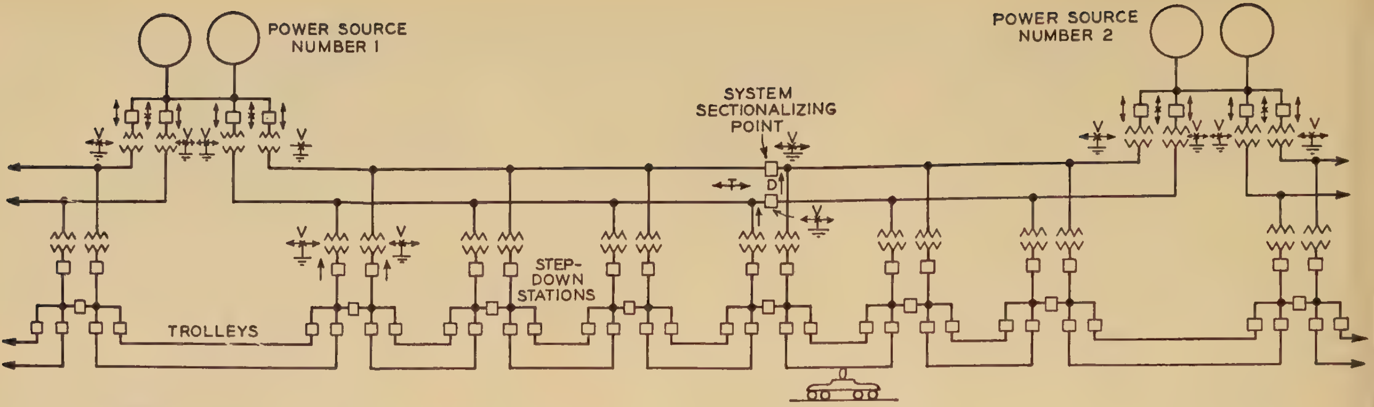


**Figure 2. Schematic diagram of power supply system showing the "looped-in" arrangement of transmission circuits and sectionalizing breakers**

These relays are further prevented from operating under extreme unbalanced load conditions by fault detector relays, actuated by undervoltage on either of the lines protected. The type *AV* fault detectors were specially developed with a view to minimizing vibration inherent in fast 25-cycle relays when operated close to the balance point and at the same time providing a high drop-out to pick-up ratio. The type *AV* relay operates in 0.10 second for a voltage 10 per cent below its setting and has a drop-out to pick-up ratio of 95 to 98 per cent.

### Backup Protection

Induction-type overcurrent relays are provided for backup protection and single-line operation. An extremely high ratio of maximum load current to minimum fault current through step-up transformers was encountered due to the following factors:

(*a*). The step-up transformers have a 250-per-cent-five-minute rating.

(*b*). Two transformers could be connected to one line at each station, greatly lowering the minimum line fault current per transformer.

(*c*). The large variation in connected generating capacity.

Complete solution of this problem required fault detectors, actuated from high voltage, and at some points automatic tap changers to change the relay setting in accordance with the number of generators connected to the bus. Even then some of the minimum faults depend for clearing upon action of the generator quick-response regulators to raise the current above the relay setting.

Figure 6 indicates schematically the relay protection at a step-up transformer station. These relays operate to trip the low-voltage breakers as indicated in figure 2.

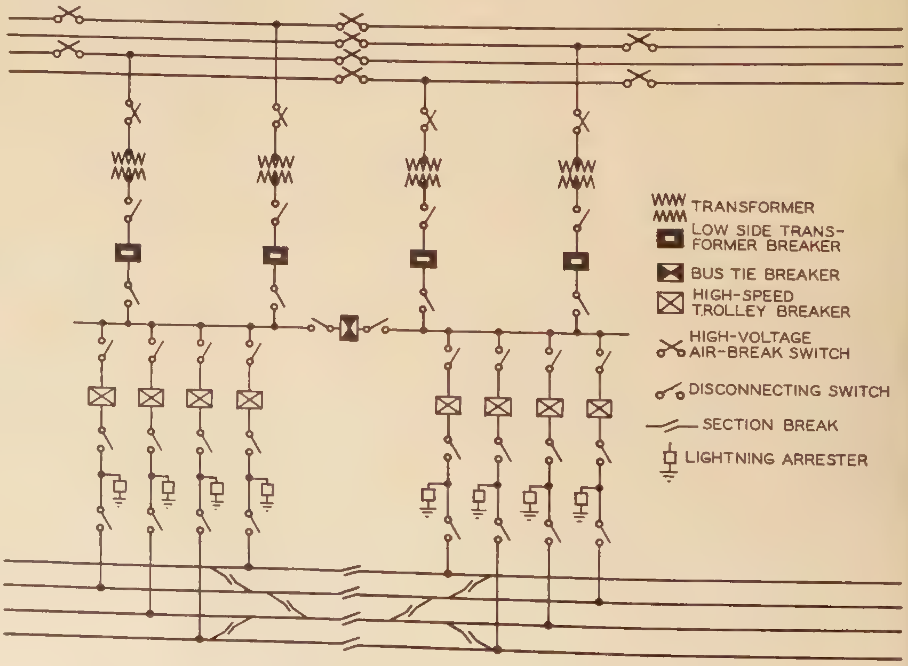
### Step-Down Stations

A typical distribution of the fault currents under minimum conditions is indicated in figure 7, and in figure 8 is given the operating characteristic of the supersensitive reverse-power directional-control overcurrent relay developed to meet the stringent requirements of this application. The relay operates rapidly on a reverse current only six per cent of the five-minute load capacity of the power transformer with which it is used. This extreme sensitivity is accomplished by increasing the energy in the directional element under low voltage and current conditions. A saturating current transformer protects the current windings under heavy load conditions. Fault detectors are used to prevent faulty tripping due to feed back to a good line and to assist in energizing a line from the low-voltage side Figure 9 indicates the reverse-power relay connections for a step-down transformer.

### High-Voltage Sectionalizing Points

At Zoo, Perryville, and Thorndale high-voltage breakers are provided for sectionalizing the system. Thorndale and Perryville breakers are operated by the step-down-transformer reverse-power relays at those locations. This arrangement facilitates obtaining selectivity on a time basis with the step-down-transformer relays since both are of the same type. The sensitivity of this arrangement in detecting a fault is indicated by the per cent voltage difference between lines necessary to cause operation. Step-down transformers are four per cent reactance, so that eight per cent voltage difference between lines circulates full load current.

**Figure 3. Single-line diagram of power circuits for one of the step-down substations**


TRANSFORMER
LOW SIDE TRANSFORMER BREAKER
BUS TIE BREAKER
HIGH-SPEED TROLLEY BREAKER
HIGH-VOLTAGE AIR-BREAK SWITCH
DISCONNECTING SWITCH
SECTION BREAK
LIGHTNING ARRESTER

he relay is responsive to six per cent of ll load current and hence to approxi- ately 0.5 per cent voltage difference be- ween high-voltage lines. This is ob- iously much closer than a differential oltage relay could be set, working di- ectly from the voltages of the two lines. he Zoo breakers are not operated for ne-to-line faults unless backup protec- on is involved.

Sectionalizing breakers of the two arallel lines are arranged to be tripped multaneously for line-to-line faults to revent serious unbalance on the good ections.

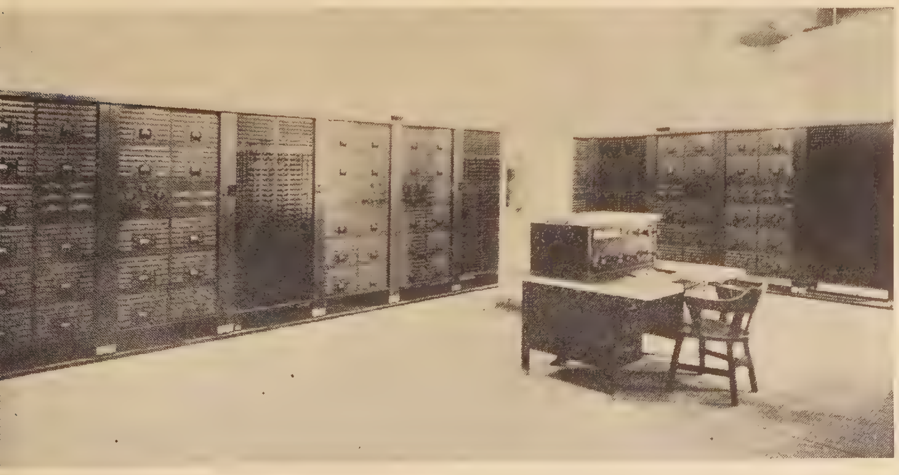
### NALYSIS OF OPERATION

During the first stage of operation after e occurrence of a fault as in figure 7 the ep-up transformer breaker nearest the ult and a number of the adjacent step- own-transformer breakers open. This roduces a redistribution of fault current ausing more reversal through the step- own transformers at other stations and esults in their opening in the second or ird stage. The majority of faults are eared in a maximum of two stages, the omplete clearing occurring in one second ade up of components as follows:

ault detector relay time —0.08 second.
elay operating times from 0.1 to 0.5 second.
reaker operating time from 0.16 to 0.20 econd.

ith certain emergency setups over-all perating times of $1^1/_2$ or 2 seconds are equired for the complete clearing of a ault. This may include the opening of 0 circuit breakers.

For faults in the Philadelphia-Perry- ille-Harrisburg area, a high-voltage ectionalizing operation occurs as the first tage followed by the operations indicated bove. While the step-up and step-down station relays are delayed by one breaker time to select with the sectionalizing point relays, the over-all clearing time is reduced due to fewer stages of step-down transformer breaker trippings. Important operating advantages result from the limitations of the extent of system affected by a fault.



**igure 4. A-c calculating board installed in Pennsylvania Station, New York City**

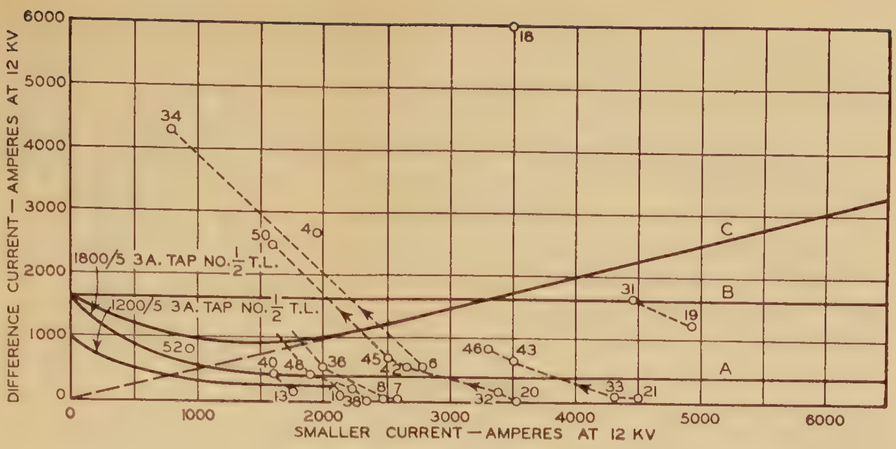


**Figure 5. Operating requirement chart for balance line relays; at Lamokin**

Note: Numbers indicate case numbers of G. and H. data

*X* = Load condition *A*. Two S.U. out same line at S.H. 100,000-kva load Philadelphia-Washington

*A* — Type *CD* relay characteristic used

*B* — Current differential of same one line trip value

*C* — Fifty-per-cent-slope percentage differential relay

## High-Voltage Lines; Line-to-Ground Faults

The step-up transformers are grounded at the midpoint of the high-voltage windings through comparatively high resistances with the result that when a line is grounded at any one point, that wire is lowered to substantially ground potential throughout its length, the other wire going to twice normal voltage above ground. This makes possible the use of differential voltage relays connected phase to ground at each step-up and step-down transformer station, resulting in prompt sectionalizing of the line, with the system setup in figure 2. It should be noted that had the transmission lines been tied past generating stations, a transmission line throughout the entire length of railroad system would have been affected in the event of a line-to-ground fault at one point. Many other similar factors occurred in which the "looped-in" arrangement of lines at generating stations had great advantages over other proposed operating arrangements.

In the area in which high-voltage sectionalizing breakers are used, two stages of ground relaying are used, sectionalizing of the faulted line occurring as a first stage followed by tripping of transformer breakers on the faulty portion only. Balanced voltage relays of induction type are used throughout, selectivity being obtained on a definite time basis.

The grounding resistor values were chosen of sufficiently low value to prevent arcing ground phenomena (the losses quickly damp out oscillations) but of sufficiently high value that with not over two or three grounding resistors connected per line, the ground fault current would keep inductive interference within permissible bounds. The 330-ohm grounding resistors limit the ground fault current per resistor to 200 amperes.

## Trolley Relay Protection

### THE REQUIREMENTS

In order to minimize inductive interference, burning of trolleys, and interference with adjacent equipment, it was decided at an early stage in the electrification to use extremely high-speed trolley protection, and accordingly one cycle (0.04 second) total clearing time was set as a requirement. A number of pos-

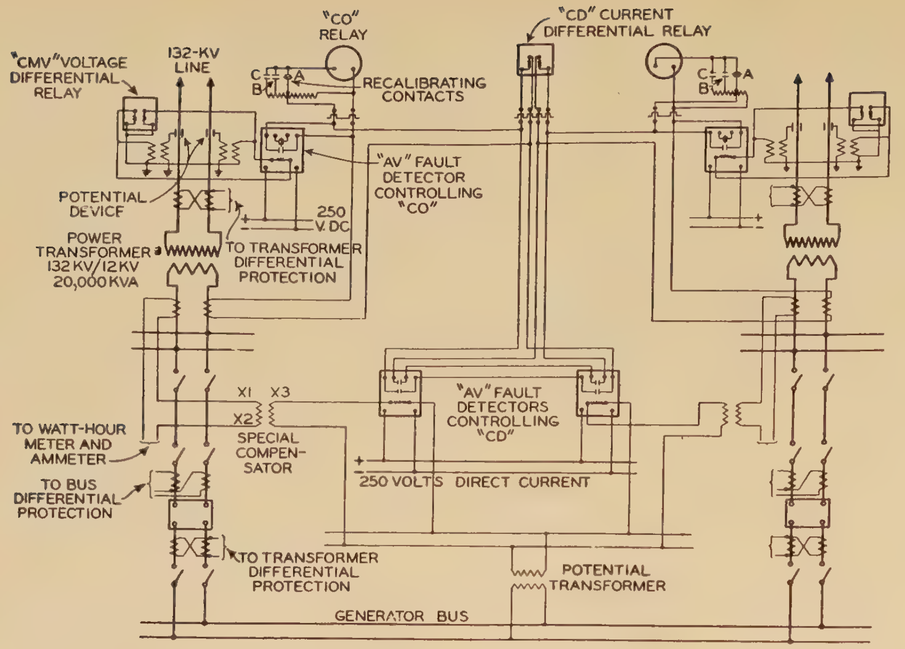

"CO" RELAY
"CD" CURRENT DIFFERENTIAL RELAY
"CMV" VOLTAGE DIFFERENTIAL RELAY
132-KV LINE
C
B
A
RECALIBRATING CONTACTS
"AV" FAULT DETECTOR CONTROLLING "CO"
POTENTIAL DEVICE
250 V. DC
POWER TRANSFORMER 132 KV/12 KV 20,000 KVA
TO TRANSFORMER DIFFERENTIAL PROTECTION
X1 X3
X2
SPECIAL COMPENSATOR
"AV" FAULT DETECTORS CONTROLLING "CD"
TO WATT-HOUR METER AND AMMETER
TO BUS DIFFERENTIAL PROTECTION
250 VOLTS DIRECT CURRENT
TO TRANSFORMER DIFFERENTIAL PROTECTION
POTENTIAL TRANSFORMER
GENERATOR BUS

**Figure 6. Typical relay connections at a step-up transformer station**

Note: Recalibrating contact *A* closed with one generator on line; *B* closed with two generators on line; and *C* closed with three generators on line

sible systems of relaying were investigated, including a 500-cycle superimposed frequency scheme, pilot-wire schemes, and the fundamental-frequency schemes finally adopted.

Two types of relay arrangement were brought out by two different manufacturers. These may be roughly differentiated as a relay type supplied by the Westinghouse Electric and Manufacturing Company and an impulse trip more or less built into the breaker operating mechanism and supplied by the General Electric Company. Both of these arrangements result in one-cycle operating time for relay plus breaker and constitute the first application of what are today known as "high-speed relays" in a-c power systems.

Each trolley section is normally fed from two ends, but with one end open, it must be capable, as far as any relaying limitations are concerned, of supplying for a short time a total load of about 40,000 kva at 11 kv, or ample power for a city of 60,000 people. This enormous moving load draws nearly twice as much current as a fault at the remote end of the trolley, which gives some idea of the problem involved in high-speed clearing of faults.

### PROTECTIVE ARRANGEMENT

Description of one of the schemes and its various elements will serve to indicate the method of solving this problem. The arrangement supplied by the Westinghouse Electric and Manufacturing Company consists primarily of an impedance relay of the high-speed type, and overcurrent elements. For longer trolley sections with heavy loads the overcurrent elements are replaced by an induction-type impedance relay, as shown in figure 10.

In general, the high-speed impedance relay, and the instantaneous current relay, where used, provide clearing for most faults, the two-cycle delay current or impedance element providing sequential tripping of the remote breaker for faults in the end zones. Thermal relays, matching the trolley heating characteristics, protect them against overload and make their full thermal capacity usable safely under any load cycle.

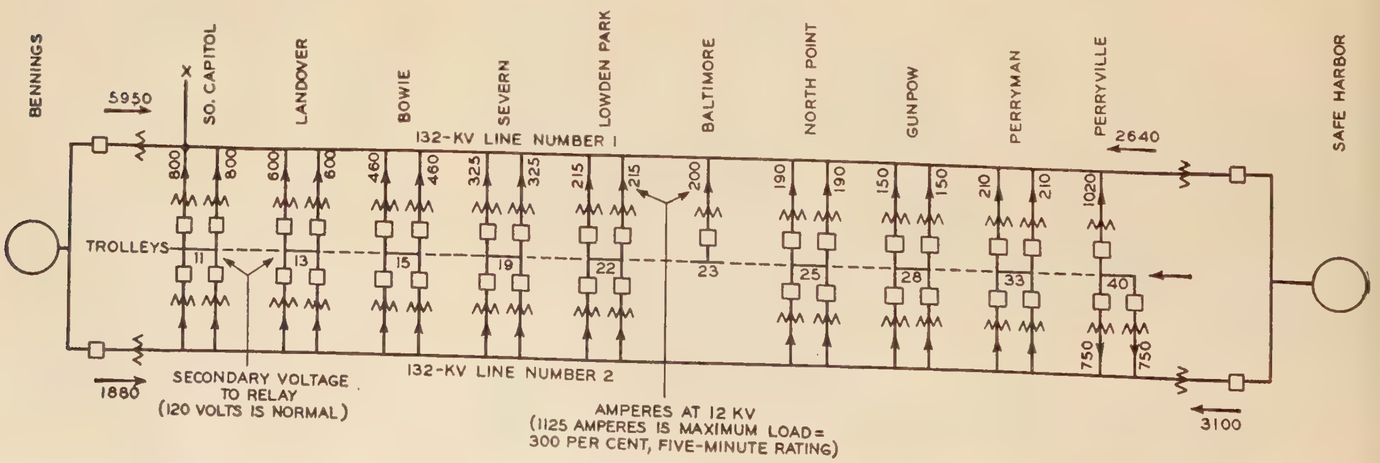
### IMPEDANCE ELEMENT

The impedance element is of the balance beam type and operates in as little as $^{1}/_{8}$ cycle on 25 cycles. This high speed is made possible by use of double voltage restraint coils, differing in time phase and resulting in an almost uniform voltage restraint. Therefore, rise of the current-coil pull above the restraint is almost instantly detected by the relay element. Advantage is taken of the mutual reactance between trolleys which results in the impedance of 96 per cent of section length being only 80 per cent of the total section impedance. This characteristic, shown in figure 11, allows setting the relay balance point within 4 per cent of the end of the section and still retaining 20 per cent safety margin. Figure 11 is based on a four-track section, the ratios being less favorable as the number of trolleys decreases.

### CURRENT DIRECTIONAL ELEMENT

The impedance element is used with a current polarized directional element comparing the direction of trolley current with that flowing through the step-down transformer bank and having a tripping zone as indicated in figure 12 in order to select the faulty trolley. It is arranged to close contacts with no polarizing current provided the trolley current is sufficient.

**Figure 7. Typical fault-current distribution under minimum conditions**



### Load Presetter

A load presetter used with the high-speed impedance relay compensates for the change in impedance caused by the presence of train loads on the trolley sections. An idea of the magnitude of this effect may be given by taking a typical seven-mile section which would have about $3\frac{1}{2}$ ohms impedance. A maximum trolley load considered is 3,000 amperes, which at an average potential of 11,000 volts would correspond to 3.67 ohms. Thus the impedance of the maximum load is roughly comparable with the impedance of the trolley section. For a fault at the one end of the trolley, the impedance looking into the other end of the trolley would be only 70 per cent as great if a maximum load were present uniformly distributed as it would be if no load were present. The load presetter compensates for this effect by providing additional voltage restraint proportional to the load.

### Transient Shunt

Since instantaneous values are being dealt with, and since in an electrical system immediately subsequent to the occurrence of a fault, a d-c or transient component may be present whose magnitude is as much as the crest value of the alternating current, a large error in impedance measurement would take place unless some measure were adopted to discount this transient current. A transient shunt was developed for this purpose. This shunt removes the transient component of the short-circuit current both from the impedance element and from the overcurrent elements of the relay equipment, making it possible to set only for the symmetrical values of current which are predictable. But for this shunt, an element set to trip down to a balance point close to the other end of the section would trip well into the other sections in the event of an asymmetrical short circuit. Transient shunts have since been applied in other high-speed relay applications.

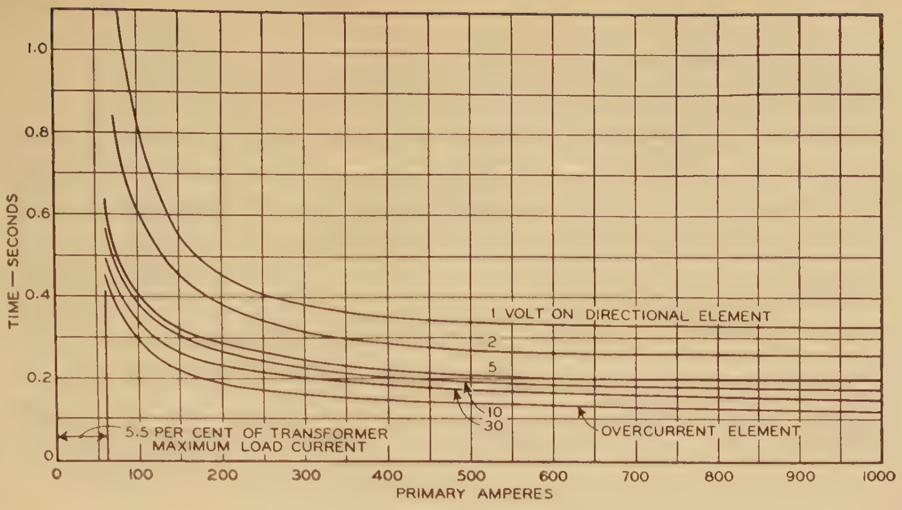


**Figure 8. Supersensitive type CR reverse power relay characteristics**

Note: Maximum load current = 1,125 amperes, five minutes. Normal secondary volts = 120

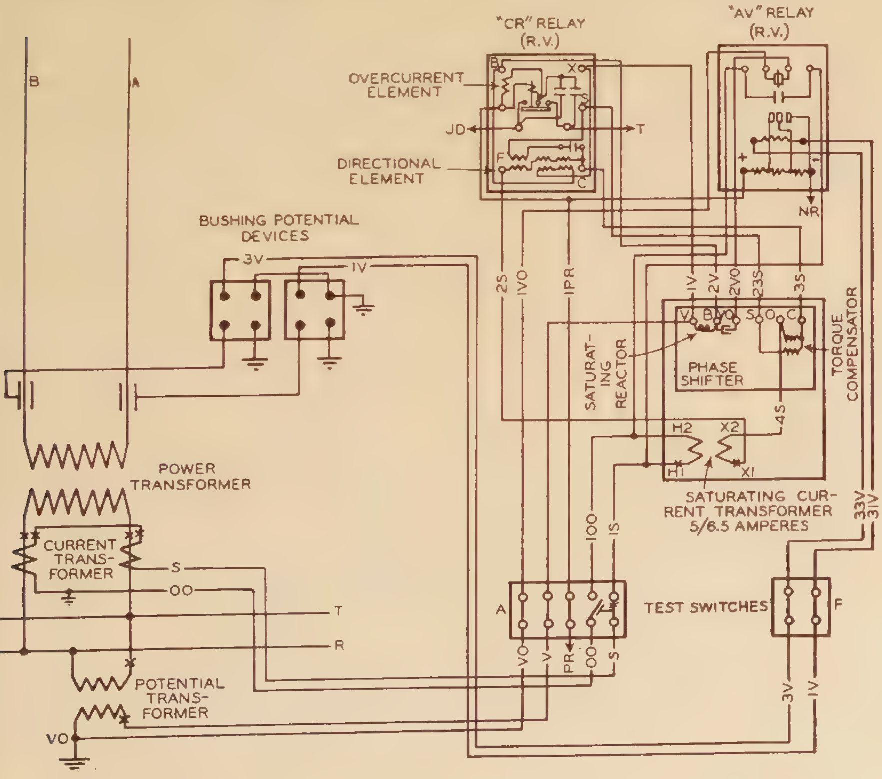


**Figure 9. Typical reverse-power-relay connections at a step-down transformer station**

### High-Speed Overcurrent Relays

Overcurrent elements of both instantaneous and two-cycle time-delay types were provided. This permits instantaneous operation for all faults which are well above through fault plus load current. The two-cycle time-delay relay is set just above maximum load current, but below those currents which are caused by the combinations of load plus heavy through fault to the next section.

### Induction-Type Impedance Relays

For longer trolley sections designed to carry heavy peak loads, discrimination between loads and faults becomes more critical and advantage must be taken of every available factor. The two-cycle-delay impedance relay balances $E^2$ against $EI \cos \theta$, and thus has maximum torque for current at a particular phase angle, which is adjusted to assist in selecting loads from faults. Thus loads may be carried of lower impedance than the relay setting provided the power factor is higher than during faults. In addition a thermal type of presetting is used which increases the setting in amount depending on the load current through the relay prior to a fault. Finally, the two-cycle delay provides selectivity with the breakers of other sections for faults outside of the protected section. This relay has inherent directional characteristics.

### Bus Protection

After several stages of development including use of induction and instantaneous types of relays measuring differential current, the majority of busses have finally been protected by percentage dif-

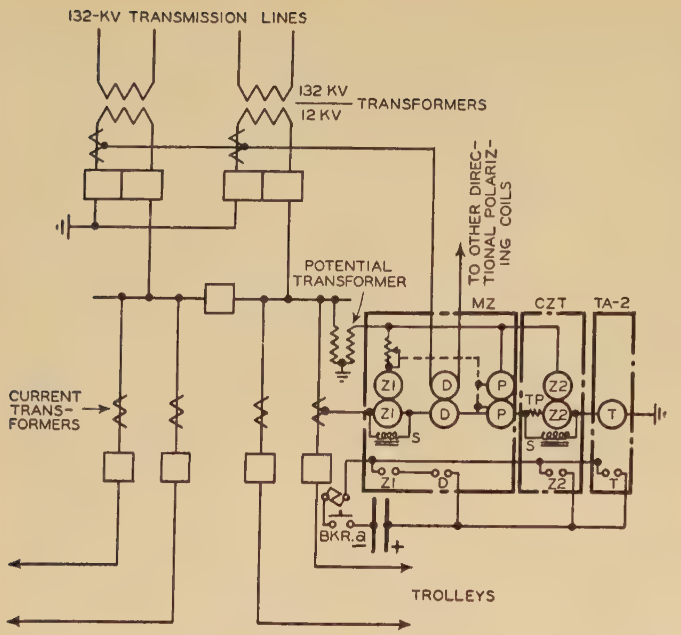


**Figure 10. High-speed trolley relays—external connections**

*Z1* — First zone impedance element, *MZ* relay
*D* — Current polarized directional element, *MZ* relay
*P* — Load presetting element, *MZ* relay
*Z2* — Second zone impedance element, *CZT* relay
*T* — Trolley thermal element, *TA-2* relay
*TP* — Thermal presetter
*S* — Transient shunt

ferential relays type *CA*-4. These are relays having three restraining windings and one operating winding. For the trolley busses, the restraining windings are associated respectively with (1) incoming transformer feeders, (2) incoming bus tie, (3) outgoing trolleys. This relay results in extremely fast clearing of bus faults and is comparatively insensitive to through faults because of the large restraint. The same type of relay has been applied with excellent success to generator busses.

### Transformer Differential Protection

The differential protection of transformers on a system which does not have high-voltage breakers at the station, is a somewhat difficult problem. It is obviously necessary to clear the entire transmission line, involving the opening of a large number of breakers, in the event of a fault involving the differential protection of a single transformer. For faults in the high-voltage winding of the step-down transformer amounting practically to line-to-line faults on the transmission system, the differential protection trips the low-voltage breaker and sets up a circuit for opening the high-voltage disconnecting switches after the fault has been cleared as indicated by the resetting of the type *CA* differential relay when the fault current is removed.

### Out-of-Synchronism

At sectionalizing points located sufficiently near the electrical center between major generating stations periodic dipping of voltage forms an out-of-synchronism indication. A "dip counter" relay was developed consisting of a counting chain of telephone-type relays actuated by the type *AV* undervoltage relay and set to trip the system sectionalizing breakers for three voltage dips within a five-second interval. For very slow pull apart, or out-of-phase conditions, overcurrent relays, operating on the totalized current of the two lines, produce simultaneous tripping of the sectionalizing breakers.

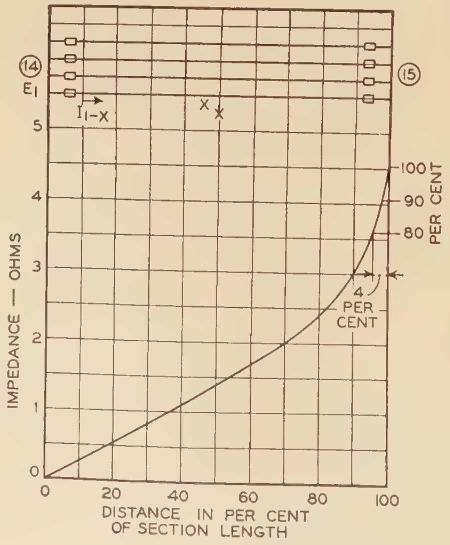


**Figure 11. Impedance versus distance characteristic of a four-track section**

$$Z = \frac{E_1}{I_{1-x}}$$

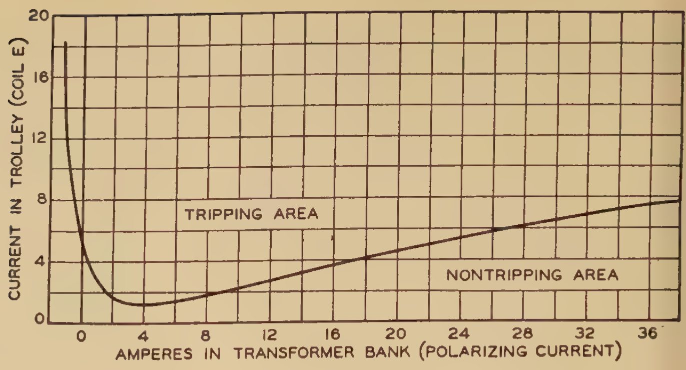


**Figure 12. Tripping characteristic of trolley directional relay**

## Undervoltage Sectionalizing

Considerable thought has been given to the confining of troubles to a particular section of the system by proper sectionalizing under certain conditions. In several instances low voltages have occurred due to various causes. This has resulted in loss of power and considerable disturbance to the system. Undervoltage relays have been installed at major sectionalizing points set to sectionalize the system automatically in event of the falling of voltage two-thirds of normal for a time adjustable between one and five minutes.

## Motive Power Unit Relays*

As the trolley fault current may be as high as 50,000 to 65,000 amperes the use of high-speed circuit breakers on the locomotives capable of interrupting the maximum faults would have been decidedly uneconomical. As a result motive power units are operated without any main breakers and rely on the substation breakers opening for major faults on the moving equipment. The locomotive is equipped with a single highly specialized relay which performs the following functions:

(*a*). For major locomotive faults, which are cleared by substation breakers in one-half to two cycles, sets up a pantograph lowering sequence but prevents lowering until the fault is cleared.

(*b*). Opens motor switches to clear motor flashovers without causing a major outage, or lowering the pantograph.

(*c*). Closes a trolley grounding switch for transformer internal faults or sustained overloads, then lowers the pantograph only after substation breakers clear.

(*d*). Does not operate ground switch or lower pantograph on transformer magnetizing inrushes in excess of fault currents. Such inrushes are sometimes encountered due to bouncing pantographs or when crossing trolley phase and section breaks.

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*Locomotive relaying is a joint development of the General Electric Company and Westinghouse Electric and Manufacturing Company in co-operation with the Pennsylvania Railroad Engineers.

Multiple-unit cars are equipped with a single device which performs less functions but which nevertheless is coordinated with the substation relaying, clearing faulty equipment from the trolley promptly after the substation breakers open and permitting prompt successful re-energizing of the trolley.

This general arrangement for clearing faults on motive power units has resulted in exceptionally good operation in the six years during which it has been in service.

## Conclusion

Most faults occur on trolleys and transmission circuits, one fault being encountered per 20 miles of transmission line per year, and one fault per 1.17 miles of trolley per year. For the complete New York-Washington-Harrisburg system this will amount to approximately 55 transmission faults (grounds and short circuits) and 1,875 trolley faults per year. A large number of these are of a nature which clear when the breakers are opened so that the affected section may be immediately reclosed.

With the protective arrangement described, entirely adequate selectivity is obtained among different protective elements of the system under normal conditions and for certain abnormal system setups necessary for maintenance. In so far as possible, the designs and settings have been planned to give proper selective action under the innumerable abnormal conditions which may occur during emergencies, while still permitting full use of the power-supplying ability of all lines and apparatus.

## Reference

1. A System Out of Step and Its Relay Requirements, L. N. Crichton. Electrical Engineering, October 1937.

# Discussion

**A. R. van C. Warrington** (General Electric Company, Philadelphia, Pa.): Mr. Harder has given a very interesting paper on his company's part of the relay protection of the Pennsylvania Railroad electrification which recalls for us in the General Electric Company the considerable developmental work we also did on the same project.

Referring to figures 8 and 9, the supersensitive directional relay at the step-down stations uses a nonlinear circuit to ensure reliable torque at low voltage. This circuit was used in our 1928 single-phase reactance distance relay though we found later that greater amplification could be obtained by using a neon lamp to provide the saturating and detuning effect at normal potential, due to its sharper cutoff.

Over 80 per cent of the trolley breakers are of General Electric manufacture equipped with impulse trip, for one-cycle interruption. Backing up the impulse trip are the *CEX* relays which, in addition, take care of faults below 1,800 amperes. These relays contain two induction-cup-type units whose contacts are in series. One unit is a directional impedance unit and the other is a directional admittance unit. This peculiar combination was necessary to produce a combined characteristic which would fit in between load and fault conditions. The settings of the two units correspond to the section length. The relay operates in one cycle to open the holding coil circuit of the breaker so that it closely backs up the impulse trip. The dying away of the holding coil flux and the opening of the breaker brings the total clearing time within three cycles.

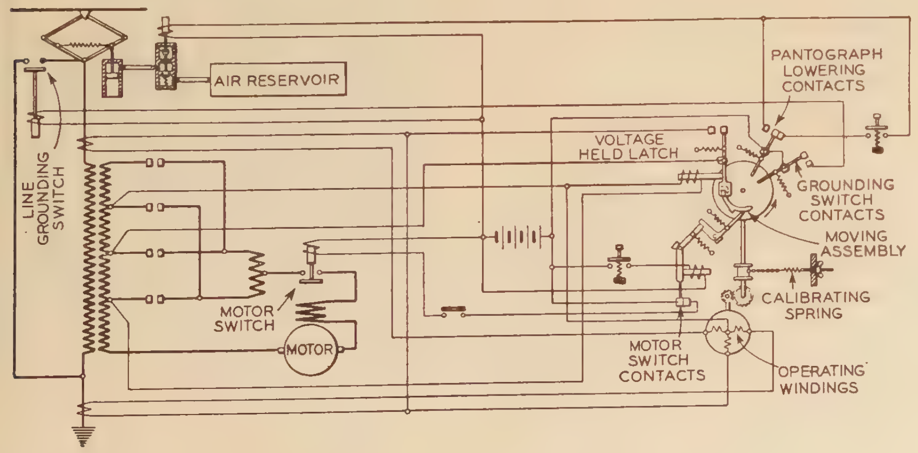
The *CEX* relay is relatively insensitive to transformer energizing transients because the operating torque of the directional impedance unit is a product of the current flux and the flux of the tuned potential circuit. It does not require a transient shunt because the d-c component produces no torque in induction relays.

The *CEX* relay gives positive directional action even on bus faults which produce zero potential because the polarizing potential winding of the directional impedance unit is tuned with a series capacitor with which it continues to oscillate for several cycles after the line voltage goes to zero. Mr. Harder did not say what precautions of a similar nature were taken in the corresponding Westinghouse Electric and Manufacturing Company directional impedance relay to ensure reliable directional action on bus faults.

In some sections the current, potential, and phase-angle conditions during maximum traffic conditions correspond to a fault within the section. In order to avoid unnecessary tripping of trolley breakers, the *CEX* relays are normally set high and are only dropped to their proper values if the rate of rise of the current indicates a fault. In order to distinguish rapid rate of rise the line current is rectified and then supplied to an auxiliary relay which supervises the protective relays. Under normal conditions the rectifiers produce only d-c which is blocked by a transformer. On the other hand, a sudden rise of current caused by a fault produces a corresponding rate of increase in the rectifier output and this increase in turn creates an impulse of current in the secondary of the transformer which operates the supervising relay.

These are a few of the many interesting problems which were solved for this unique application.

Figure 13. Schematic diagram of locomotive relay



**C. Romanovsky** (nonmember; General Electric Company, Philadelphia, Pa.): E. L. Harder's paper on relay protection for a railroad system is of great benefit to engineers interested in a-c railroad electrification.

Other relays than those described in Mr. Harder's paper have been supplied by the General Electric Company for the solution of numerous difficult problems of system protection on the Pennsylvania Railroad electrification projects.

Among these were relays of very strict requirements for the differential protection of the 132-kv underground oil-filled cable at Baltimore and Washington. These relays must stand 5,000 amperes primary for five seconds and operate on faults as low as 30 amperes primary.

The relays operate over a two mile run (average) of number 10 pilot wire, and are meeting the following requirements:

*The relays must not operate on:*

| | | |
|---|---|---|
| *A.* | Five-minute load | up to 300 amperes |
| *B.* | Through short circuit | up to 5,000 amperes |
| *C.* | Through ground fault | up to 800 amperes |
| *D.* | Charging current | up to 20 amperes |

*The relays must operate on:*

| | | |
|---|---|---|
| *A.* | Short circuit in cable | from 30 to 5,000 amperes |
| *B.* | Ground on cable | from 30 to 800 amperes |

The relay operates on a sensitive percentage differential principle. It contains an operating and a restraining circuit. The current transformers at the two ends of the cable are differentially connected with respect to the operating coil so that on a fault in the cable, current will flow in the operating coil and thus operate the contacts. During an external fault, the current flowing in the secondaries of the current transformers and in the restraining coil opposes the effect of any operating current which may result from slight difference in the secondary currents of the current transformers. This restraining action prevents operation on through faults.

For the New York zone, where direct current is superposed on a-c apparatus due to common rail return circuit, relays were developed to prevent opening motor-operated disconnecting switches when more than 25 amperes alternating current with superposed 750 amperes direct current is flowing in the circuit and be able to withstand short-circuit currents of 50,000 amperes.

In order to reduce the cost of electrical equipment in large station areas, groups of low-interrupting-capacity normal-speed breakers are used for the isolation of faults on yard and passenger station feeders. Each group of from two to five breakers is fed by a high-speed high-interrupting-capacity (master) breaker which clears the fault. The high-speed breaker is relayed similar to other trolley breakers for discriminating between load and fault currents and for selective operation.

A relay was developed for selecting the faulted trolley before the master breaker opens so that when this breaker has cleared the circuit and the current through the low-interrupting-capacity breaker on the faulted trolley has fallen to a safe value, the relay permits the low-interrupting-capacity breaker to open. After the opening of the low-interrupting-capacity breaker, the relay closes the master breaker, and thus restores service on the unfaulted trolleys.

The operation of a great number of trolley-sectionalizing disconnecting switches offered an interesting problem. They were to be operated from distances up to five miles by 110-volt 100-cycle power taken from 6,600-volt signal lines at points near the disconnecting switches. The current through the control cable was limited to 0.15 ampere. Control and position indication of the disconnecting switches was to be accomplished over the smallest number of wires. Undesirable operation and false indication of switch position by induced currents during short circuits on the trolley system was to be avoided. Hazard of shock to operators and maintenance men was to be removed.

A relay and control scheme was developed using only four wires for each switch.

Small 110/220-volt insulating transformers with midpoints grounded are used rather than impedance coils. With this scheme high induced potentials cannot stress the insulation of control devices.

**L. N. Crichton** (Westinghouse Electric and Manufacturing Company, Newark, N. J.): There is an enormous amount of power available on this system so that the relays and circuit breakers must be capable of safely withstanding very heavy short-circuit currents. On the first units of this electrification the anticipated loads were small enough and the sections of trolley wire were short enough so that the load current never exceeded the minimum short-circuit current. It would, therefore, have been possible to protect these sections by means of instantaneous overcurrent relays set to operate on a high current and time-limit overcurrent relays set to operate on a low current. Such relays were actually installed and in addition instantaneous impedance relays were installed to secure maximum possible simultaneous clearing of faults.

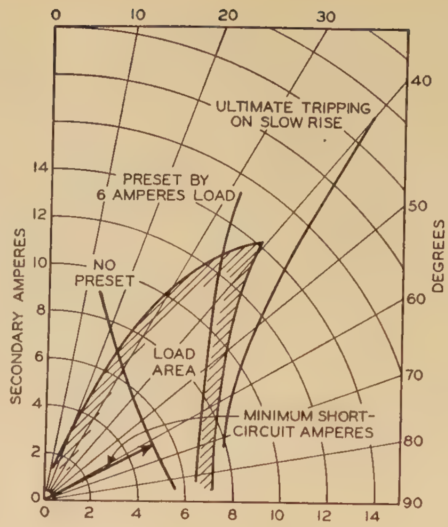


**Figure 1. The load characteristics and the tripping point of the type CZT impedance relay for long trolley section at varying phase angles and load conditions**

Now the loads are heavier and the newest electrified sections are much longer so that the load current under some conditions is greater than the short-circuit current. The anticipated loads and minimum short-circuit currents are shown in figure 1 of this discussion. This curve also shows the tripping characteristics of the time-limit impedance relay mentioned by Mr. Harder. It will be observed that the relay will trip if the minimum short-circuit current is applied when no load exists. If a load has existed for several seconds, the relay will trip when an additional sudden increase in current is applied. Finally, the relay will trip if current is either gradually or quickly added above the values shown on the curve at the extreme right. This adjustment differs for every different length of line.

This relay has an adjustable time limit of two cycles or more and is intended to protect only the far end of the trolley wire. A photograph of this relay is shown in figure 2 of this discussion. The thermal element which increases the setting of the relay when the load comes on is the nickel wire shown at the front of the slider. This picture shows the complete relay except for an external resistance in the potential circuit and a shunt reactance in the current circuit. This relay is of the induction type and is inherently directional.

The greater length of the trolley wire is protected by an instantaneous impedance relay, a photograph of which is shown in figure 3. This relay is not inherently directional and, therefore, contains a directional element shown in the upper left, as well as the impedance element in the upper right, and the load presetter in the lower left. This load presetter is a small motor operated by the volt-amperes in the line. When the load increases, this motor moves and cuts resistance out of the potential coil circuit so as to increase the voltage restraint.

This high-speed relay and its associated breaker clears the usual trouble in one cycle. This requires that the relay cannot have more than one-fourth cycle in which to operate and sometimes the operation is much faster than that. The result of this fast operation is that even the heaviest of short circuits cannot be observed at the generating stations and it is seldom that any burning can be found on the trolley wires. From the figures given in Mr. Harder's paper it can be calculated that the average section of trolley wire has six short circuits per year, about five of which are cleared by the high-speed relays and one by the two-cycle time-delay relay.

It was difficult to design a relay to work accurately at this high speed because of the transient in the circuit. Although this transient has practically disappeared in two cycles, it is of enormous consequence during the first one-fourth cycle when the relay must complete its work. The problem was solved by the invention of the transient shunt, the use of which has since been extended to other types of high-speed relays.

**D. R. MacLeod** (General Electric Company, Erie, Pa.): Mr. Harder's presentation of the relay protection of the power supply for the Pennsylvania Railroad electrification brings out the interesting contrast between the comparatively leisurely manner (seconds) in which a high-voltage transmission fault is cleared and the get-rid-of-it-quick (cycles) attitude toward trolley faults. The high level of insulation adopted for the 132-kv and 44-kv lines and the adequate ground wire and counterpoise protection is one justification for this philosophy. The ability to isolate any section of transmission between substations with only temporary interruption of power to these substations, even where only one line is available, is another justification. There were, of course, additional reasons for these engineering decisions since relaying was not the dominant factor in designing this transmission line and trolley system. While the trolley is provided with a high level of line insulation and is shielded by the transmission circuits the data given in this paper show that 97 per cent of the faults occur on the trolley. This relation between transmission and trolley faults was expected when the system was designed.

The devices used in the General Electric

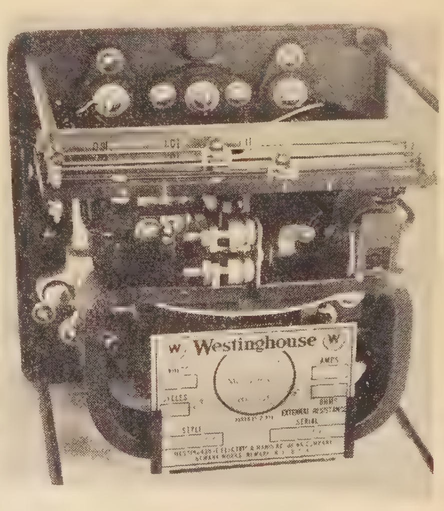


**Figure 2. Type CZT time-limit impedance relay with load presetting**

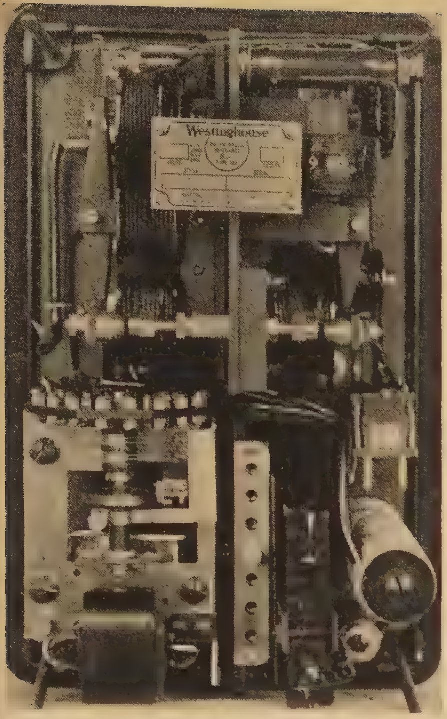


Figure 3. Type MZ high-speed impedance relay with load presetting

trolley relaying scheme are described in the discussions presented by Messrs. Romanovsky and Warrington.

There are important differences between this system of relaying and that described by Mr. Harder. Our approach to the problem has been based to some extent on theoretical studies such as Mr. Harder has described but we have given even greater consideration to experiences in the field. The majority of trolley faults occur in connection with the operation of the rolling stock and therefore we have given particular attention to the troubles which develop on these equipments. Our relaying has been designed to allow the greatest possible freedom in the design of the rolling-stock equipments which are always handicapped by space limitations.

The control schemes on different groups of locomotives differ in detail. On one group it is possible for one locomotive to have the impedance characteristics of three locomotives for an appreciable time before the operation of the ground switch. The distinguishing characteristic is however the low power factor under this particular condition. When the ground switch operates this "load" goes to zero and the impedances measured by the trolley relays are the same as if the load had not been present. If the locomotive was operating double headed the fictitious load would be equivalent to four locomotives accelerating and power factor will be entirely different from what may be expected with four normal locomotives. After the grounding switch closes there is a sudden increment of current due to the fact that the locomotive impedances are reduced to zero and this increment is always in excess of the notching increments on any of the rolling stock equipments.

Other examples of this general type based on actual experience in the field might be recited but it serves to show why our relaying system does not attempt to take advantage of presetting the relays in accordance with the characteristics of the load.

Mr. Harder claims that the transient shunt makes it possible to set the high-speed relays only for the symmetrical values of current which are predictable. Our studies of the various types of energizing transients which can occur on a locomotive load show a wide variety of wave fronts which would require a complicated network to handle. The symmetrical components of these transients are not predictable as they are complicated by the induction-motor load on the secondary of the locomotive. There is some inherent shunting of the transient in the impulse scheme but we do not take advantage of it. No shunting is necessary with our impedance relay. The settings of the impulse trip have been determined by field experience during the ten years that it has been in operation on this electrification.

Our first line of defense is the impulse trip. This scheme was originated by J. W. McNairy and is described by him in AIEE TRANSACTIONS, volume 47, October 1928, page 1276. The second line of defense is the distance relay described by Mr. Warrington which can be set to cover the entire distance between substations. It is not desirable to take advantage of the mutual impedance between trolleys (see figure 11 of Harder's paper) because this mutual may not be there when it is needed most and it is possible to visualize conditions when it is in the wrong direction. On the Harrisburg electrification a few rate-of-rise relays were provided for those sections of the railroad where it was feared that abnormal operating conditions might show that it is desirable to have an additional means of discriminating between a load and a fault. The experience gained with these equipments will be of value in working out adequate protection for the trolleys as substation spacings are increased. However, it should be noted that the trend of operation practices on this electrification is in the direction to make the relaying problem considerably easier than was first visualized.

An important consideration in distance relaying is the variation in the impedance characteristic of a locomotive with variation in trolley voltage. It may be shown from a consideration of the characteristics of the a-c series motor that for a given tractive effort, field connection, and power factor the impedance as measured at the pantograph of a locomotive varies as the square of the applied voltage and that for a given tractive effort the minimum impedance varies directly as the applied voltage. The minimum impedance of two locomotives pulling the heaviest freight train which we know of from Enola (across the river from Harrisburg) to Waverly, N. J., is of the order of ten ohms at approximately 80 per cent power factor with a trolley voltage of 11 kv. If the freight train is half the size but has two engines on it to get motive power to the other end of the line, the minimum impedance will probably be the same as with the heavier train. The locomotives in passenger service present the real problem. A train which could operate with one engine may be double heading and the engineer may elect to accelerate rapidly. The minimum impedance may be seven ohms and the power factor near 85 per cent. As the train speeds up to running speed in passenger service, the power factor goes above 90 per cent and the impedance increases. The impedance of the double-headed passenger train at the power factor corresponding to the angle of the line will probably be the same as that of the heavy freight train. This impedance is, of course, much greater than the minimum impedance. In the case under consideration it would be approximately 12.5 ohms. If the voltage falls to 8,500 volts the impedance of the train at the power factor corresponding to that of the line may be 7.5 ohms. Because of the rapid acceleration of the passenger train the highest values of current are only experienced for a matter of seconds so that the trolley is not overheated. The distribution of passenger trains running with several sections is considerably closer than is usual in freight operation. It is, of course, difficult to predict what the groupings of trains will be under abnormal conditions of operation and therefore the railroad engineers specified certain conditions as a basis for working out the relay problem. The General Electric Company's system of trolley relaying was given the greatest flexibility that modern relaying permitted as it was recognized that future developments might prove that the specified conditions were inadequate.

**W. A. Lewis** (Cornell University, Ithaca, N. Y.): Certain phases of the paper by Mr. Harder appear to justify further amplification and emphasis. It is stated in the paper that prior to the advent of the a-c network calculator, the short-circuit currents were determined analytically. It has been the practice for a number of years on a large number of systems to use the d-c calculating board for the determination of short-circuit currents, and some question may arise as to why the d-c calculating board could not be used in this case. The d-c calculating board introduces the fundamental assumption that the phase angles of the various impedance elements entering into the network are so nearly the same that they may be assumed equal without introducing appreciable error in calculation. In this case, the frequency is 25 cycles, with the result that the reactance components are less than half of what they would be if the same circuit elements operated at 60 cycles. Because of the relatively large resistance components in the transmission circuit elements, the ratio of reactance to resistance is quite low at this frequency, and the phase angle of the circuit element is therefore relatively small, in the order of 45 degrees. On the other hand, the phase angle of the transformer elements remains quite high, in the order of 80 degrees or more, with the result that the phase angle of the transformer elements is much greater than of the line elements. For a fault in any given location there are numerous parallel circuits involving the step-down transformers in the several substations, and the division of current between these parallel branches is important in the application of the relays. Because of the wide phase-angle difference just described, it was not possible to obtain sufficient accuracy in a solution made on the d-c calculating board, and accurate representation on a miniature system was therefore not possible until the a-c network calculator became available.

Another feature deserving of mention is the mutual impedance between the several parallel trolley-rail circuits, due to inductive coupling between the parallel trolleys, and to the common use of the rail and earth in the return circuit. Mutual impedances of this character are difficult to represent on a d-c calculating board when the number of parallel circuits exceeds two, as it does on the Pennsylvania Railroad when more than two tracks are involved. This problem can be handled readily on the a-c calculating board by the use of mutual transformers which have previously been described.

The description of the protection of the extensive power supply system for this railway invites a comparison with the relaying of public utility systems. Two important differences may be noted between the two different forms of power supply. With the railway system, the load is distributed along the trolley circuits, and moves rapidly from one location to another. This means that the currents and the impedances measured by the relays for a short circuit in a given location will vary considerably depending upon train location and the load drawn at the time the fault occurs. This is in contrast with the public utility system in which the major load is almost always drawn from fixed substation locations usually at bussing points, and does not move rapidly from one place to another. The so-called "load presetting device" which recalibrates the relays as a function of the load just prior to the fault is an unique and interesting method of overcoming the problem encountered.

The second notable point of difference is the use of high-voltage lines with the large number of substations tapped in without the use of high-voltage breakers at any of the substations. Although there has been a certain tendency to eliminate the high-voltage breakers in the power system, it has never been practiced to anything like the extent utilized by the railroad. The high speed of protection obtained with this layout, which appears very complicated to the relay system, is quite notable. The development of the very sensitive reverse-power relays indicates what can be done when the necessity arises. The absence of high-voltage busses makes possible the very unique use of balanced voltage relays for the protection and isolation of ground faults.

It is also interesting to note the developments in the railway field which have found application in the utility field. The most notable of these is the use of the high-speed balanced-beam type of impedance relays. Although the principle was not new at the time, the railway installation represented the first installation in the United States of the high-speed impedance relays operating on this principle. Impedance relays operating on the same principle are now the accepted means of providing the highest speed phase-to-phase protection on utility systems, being used in the majority of distance relays, and being the backbone of the carrier-current relay system which has found the greatest favor in the last few years.

**E. L. Harder:** The supplementary information contributed by the several discussers on the trolley relays is the most valuable addition, making the paper a rather complete description of the over-all relay system from generator to motive power equipment. The paper had covered the protection of eight main system elements but had described only the Westinghouse form of the trolley relay protection. The discussion completes the picture of this particular element of the relay system. Strangely enough, however, the high-voltage system represents by far the more difficult and complicated relay application problem. Certain questions and points are raised by the discussers requiring additional information which is given in the following.

Mr. Warrington states that the *CEX* relay operates in one cycle. We assume that this refers to its operating time for faults close to the relay since if it operated with this speed for faults at the remote bus it would trip also for faults on that bus or in the next section. The delayed relay time mentioned in the paper for the *CZT* time-delay impedance relay is given for fault at the remote bus.

He has requested to know how the Westinghouse company has solved the directional-relay problem which exists on a single-phase system susceptible to solid faults. A current polarized directional relay was used in which the totalized current of the step-down transformer supplies the polarizing element of the relay as shown in figure 10. Thus voltage is not required on the directional element. Its characteristics are shown in figure 12 of the paper.

Mr. Romanovsky describes the protection of the oil-filled cables and lists the setting requirements. It would of course have been interesting to go into this detail for other of the relays but the space limitations of the Institute paper do not permit. He has described the manual remote control of sectionalizing switches. We fail to see what connection this has with a paper on protective relaying.

In Mr. Crichton's discussion, figure 3 shows the current polarized directional element mentioned above. His explanation of the difference in the importance of transient shunt for a fractional cycle relay as compared with a relay operating in one or two cycles is particularly significant.

Mr. MacLeod mentions that the normal clearing times (one or two seconds) used on the high-voltage system are justified by the ability to sectionalize and obtain only temporary interruption of power to substations. Out of 61 step-down substations only three received power from a single line and these three have adjacent stations fed from both lines with consequent trolley feed. Therefore in almost all cases faults can be relayed out without interfering with loads at all. At the three stations fed from a single line the question of whether the line is cleared in a cycle or a second does not affect the duration of time required to sectionalize faulty line and re-energize the station. It does not appear that the ability to isolate any section of transmission has anything to do with the justification of normal-speed relaying. The matter of prime importance is that the clearing of high-voltage faults does not interrupt power to the trolley and consequently higher speeds are not essential.

He questions the ability of the transient shunt to make possible setting for symmetrical component of current only and mentions different wave fronts of locomotive inrush current. The high-speed impedance-relay setting is actually based on the symmetrical component of current and the relay is set to produce simultaneous tripping over 80 per cent of the section length. In view of the large number of trolley faults (one per mile of trolley per year) this is unquestionably proof of the efficacy of the transient shunt. There is a disagreement in view of the transient shunt in its function. Mr. Warrington assumes (correctly) that the transient shunt removes d-c component and states that his *CEX* relay does not require a transient shunt because the d-c component produces no torque in induction relays. Mr. MacLeod states that their studies "show a wide variety of wave fronts which would require a complicated network to handle." This would seem to require some further explanation of the transient shunt action.

If a sine-wave voltage is impressed on a resistance-inductance circuit at some particular instant of time a current flows which has a d-c component dying out with a certain time constant $L/R$. If this process is reversed and the same current (except in secondary terms) is passed through the same resistance and inductance (or values proportional thereto) the sine-wave voltage (except in secondary terms) will be reproduced, without any d-c component. If then this voltage were used to supply a pure resistance relay the relay current would be proportional to the symmetrical component of line current only. The exact theory upon which the design is based takes account of the actual relay burden in determining the correct proportions. However, the foregoing picture is a quite accurate representation of what occurs. It is apparent that the shunt is effective right from the start and hence usable on a relay which has an operating time of less than one-fourth cycle. The time constant of the d-c transient on the Pennsylvania Railroad trolley circuits is about one-third cycle for fault at the remote end of the trolley. The transient is therefore not of much importance anyway on the *CEX* relay which Mr. Warrington states operates in one cycle. We would expect it to have some effect on the impulse trip which operates in a fraction of a cycle. It is possible to obtain a much larger zone of simultaneous high-speed action of breakers at both ends of the line through the use of the transient shunt.

Mr. MacLeod states that it is not desirable to take advantage of the presence of the paralleling trolleys because they may not be there when needed. Mr. Boehne pointed out in his oral discussion that advantage is taken of the paralleling trolleys in the General Electric scheme in preventing the impulse trip from operating for faults at the remote bus. The same objection applies in both cases. Also, in both cases the answer is the same. The advantages which accrue under all normal and reasonable abnormal conditions are well worth suffering the slight adverse effects under extreme abnormal conditions.

Mr. MacLeod also suggests that the mutual might be in the wrong direction. This seems like an unnecessary suggestion to make without good cause. For a fault near the remote end of a trolley, which is the only condition under which mutual impedance between trolleys affects the relay one way or the other, currents flow in the same direction in all the trolleys, namely, toward the fault. Thus the currents in the adjacent trolleys acting through the mutual impedances increase the effective impedance of the relayed trolley which is as desired. When the remote breaker opens, if the fault is between the relay and the remote station, currents in the other trolleys reverse and flow toward the relay and thence over the faulty stub end trolley to the fault. Again this is also desired. The effective impedance is lowered by the mutual and the high-speed impedance-relay element which was set short of the remote bus when all breakers were closed is actually able to clear a fault at the remote end of the trolley as soon as the remote breaker opens, by taking advantage of the reversal in current direction in the parallel trolleys. This covers all of the possible conditions. Thus the mutual voltage drop is sometimes in the reverse direction but never in the wrong direction as Mr. MacLeod suggests.

The implication that variation of locomotive impedance as the square of line voltage depends on series-motor characteristics, is somewhat misleading. Given *any* type of load operating at a given voltage on the secondary of the transformer; raise the primary voltage, and change the transformer taps so that the secondary voltage is the same as before; the impedance (ratio of voltage to current) as viewed from the primary side of the transformer will have increased as the square of the voltage. This is for the simple reason that the turns ratio increases directly as the voltage. Impedance varies as the square of the turns ratio.

The really important thing is that the series motor behaves like an impedance at all, that is, that when the applied voltage is suddenly raised or lowered, current raises or lowers proportionally in a negligible part of a cycle. For example, if the applied voltage falls to zero the motor current falls to zero so fast that the difference in time is not distinguishable on a film with cycles spread out to one inch. This would not be the case at all with synchronous motors for example, which would feed heavy short-circuit current in the trolley when it is faulted.

Mr. Lewis has compared the railway transmission system with conventional power-system practice. His broad experience in both fields makes this comparison of particular value.

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# Fiber Glass—An Inorganic Insulation

By F. W. ATKINSON
MEMBER AIEE

FIBER-GLASS textiles have achieved considerable importance in the field of electrical insulation since their introduction to industry a few years ago. Design engineers are finding in them a solution to special problems which heretofore had been solved only inadequately or temporarily at best.

It is a well-known fact that the output rating of a piece of electrical equipment is limited first of all by the temperature its insulation will stand without excessive deterioration. The commonly used types of organic insulation, that is, cotton, silk, linen, and paper, rarely permit a rated temperature rise greater than 55 degrees centigrade over an ambient of 40 degrees centigrade. Where higher temperatures were unavoidable, asbestos has been used if the attendant space factor was not prohibitive and the low tensile and dielectric strength were not of great importance. Mica in many different forms—as the outstanding class *C* insulation—has been used extensively, but the lack of mechanical strength and the high cost have imposed sizeable limitations.

Another never-quite-solved problem has been that of moisture absorption in fibrous insulation. And no amount of treatment or impregnation has as yet effected a perfectly moisture-proof flexible insulation that also is heat and oil resistant.

It is in the providing of a more satisfactory solution to these two specific problems of heat and moisture resistance that fiber-glass insulation, up to the present time, has contributed most extensively. Other characteristics such as chemical stability and mechanical strength coupled with heat and moisture resistance are proving increasingly valuable. Concrete examples of the resistance of fiber glass to the effects of corona together with outdoor moisture conditions have come to light recently in connection with its use on neon-sign lead wire.

Glass as an electrical insulator has been used for many years, but only comparatively recently has it achieved flexibility. In so doing it has become the first totally inorganic textile—one whose characteristics observed in the laboratory and in operation have proved it to be as good as, and in most cases superior to, other fibrous materials used for electrical insulation.

The fibers are pure glass and the fundamental process which converts the original batch into molten glass is the same as that used in making milk bottles or window panes. Some of the batch constituents are also the same. The important difference between ordinary glasses and those used in making electrical insulation is that the latter contain no monovalent substances and are alkali free. To be alkali free is an essential property because alkali leaches to the surface, thus presenting an ionizable salt which, under conditions of high humidity, decreases the insulation resistance considerably. This phenomena is aptly illustrated by tests on a low-alkali glass tape and a similar one which was made of alkali-free glass. After 72 hours in a constant relative humidity of 90 per cent at 100 degrees Fahrenheit, the insulation resistance of the alkali-free glass was 40 times that of the low-alkali glass.

The data herein are presented to indicate some of the more important properties of fiber glass and some of the fundamental reasons for its acceptance as an answer to specific problems in the field of electrical insulation. These data are discussed in considerable detail and comparisons are made to other commonly used types of insulation.

Glass fibers are produced in two distinct types, staple length and continuous. The former are comparatively short fibers from 8 inches to 15 inches long and approximately 0.00025 inch in diameter. Fabrics made from these short fibers resemble cotton or woolen ones. The continuous fibers, as their name implies, are produced in continuous lengths limited only by the size of the spools upon which they are wound. They average 0.0002 inch in diameter.

The staple-length forming apparatus consists mainly of a small electric resistance furnace, a steam blower with nozzles for producing high-speed steam jets, a chain conveyor, and a packaging machine. One-third-ounce glass marbles are fed into the top of the furnace automatically one at a time, and are melted. The furnace is made of high-temperature refractory material with the exception of the bottom which is made of a precious metal alloy. The molten glass passes through small orifices in the alloy from which point the resulting filaments are blown downward onto a drum-type conveyor by high-velocity steam jets. Lubricating oil is sprayed onto the fibers as they are being blown downward onto the chain in order to minimize the interfiber

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Acknowledgment is made to R. A. Corby, assistant, for assembling the data for this paper.

**Table I. Breaking Strength in Pounds (Minimum of at Least Five Readings on Each Sample) of Staple- and Continuous-Fiber Alkali-Free Glass Tapes at Room Conditions**

| Width (Inches) | Thickness (Inch) 0.010 | 0.015 | 0.020 | 0.025 |
|---|---|---|---|---|
| **Staple** | | | | |
| 1/4 | 59 | 85 | 105 | * |
| 3/8 | 68 | 108 | 119 | 132 |
| 1/2 | 110 | 158 | 183 | 231 |
| 3/4 | 150 | 167 | 245 | 290 |
| 1 | 182 | 250 | 305 | 346 |
| 1 1/4 | 268 | 298 | 360 | 400 |
| **Continuous** | | | | |
| 1/4 | 70 | * | 186 | |
| 3/8 | 91 | * | 265 | |
| 1/2 | 133 | 285 | 346 | |
| 3/4 | 220 | 322 | 440 | |
| 1 | 280 | 494 | 595 | |
| 1 1/4 | * | 610 | 850 | |

* These sizes not available for test.

friction during the subsequent processing. Being prevented from blowing off the chain by air suction beneath it, the mat of fibers is then drafted into a single sliver by winding the latter on a two-inch-diameter paper tube whose linear velocity is greater than that of the drum conveyor. The tubes of sliver are then placed on textile spinning machines where the yarn is spun in the same manner as cotton or wool yarn.

The continuous process differs from the staple process mainly in the manner in which the fibers are drawn from the furnace. Here no steam jets are used. The fibers (102 of them) are drawn together into a single filament and are pulled down from the furnace mechanically by winding on a bakelite tube fastened to a spindle revolving at high speed. Lubrication is accomplished by passing the filament over an oil-soaked felt pad. The filament made up of 102 individual fibers is wound on the tube at the rate of 6,000 feet per minute. (One marble will produce over a mile of the filament or about 120 miles of individual fiber.) At this point the product is ready for the twisting operation in the textile fabrication sequence. The yarn and fabrics produced from continuous fibers resemble silk or rayon in appearance.

In general, staple-fiber products are preferable where a heavy type of insulation is required. Continuous fabrics have their advantage where space factor, impregnating qualities, or appearance, are of primary importance.

## Tensile Strength

This is one of the more important properties of electrical-insulation textiles and perhaps the most important mechanical one, not only because of the obvious reason, but also because it provides an excellent means of measuring the effect of other test and operating conditions upon fibrous materials. For instance, the effect of heat, acids, weathering, etc., may be evaluated by noting the corresponding change in tensile strength.

Glass fibers of diameters such as are used in making textiles for electrical insulation have extremely high breaking strength. The value for individual fibers of the order of 0.0002 inch in diameter has been shown to be in excess of 1,000,000 pounds per square inch. No other textile fiber approaches this figure. Tests also show that woven glass fabric is stronger than other textile fabrics.

Table I shows the minimum breaking strength of some of the standard staple-fiber and continuous-fiber alkali-free glass tapes used for electrical insulation.

Table II shows the breaking strength of standard 0.010 inch by 1 inch staple-fiber glass tape after subjection to different temperature cycles simulating those which a piece of electrical equipment might encounter under severe operating conditions. It will be noticed that after a temperature cycle of 500 degrees Fahrenheit for 30 minutes each day for ten consecutive days the tape still retained 79 per cent of its original strength. After 400 degrees Fahrenheit for 30 minutes, its strength even increases slightly, probably due to the decreased viscosity of the processing oils permitting a greater equalization of stress among the individual fibers.

One accepted test of heat-resistant insulation is to subject it to a temperature of 300 degrees centigrade for five minutes. A series of these tests has shown that continuous-fiber glass tape retains from 87 to 92 per cent of its original strength and staple-fiber tape retains from 85 to 95 per cent. Similar tests showed that underwriters' grade asbestos tape loses approximately 46 per cent of its original strength. (After subjection to this temperature, cotton tape did not have sufficient strength to permit tensile strength tests.)

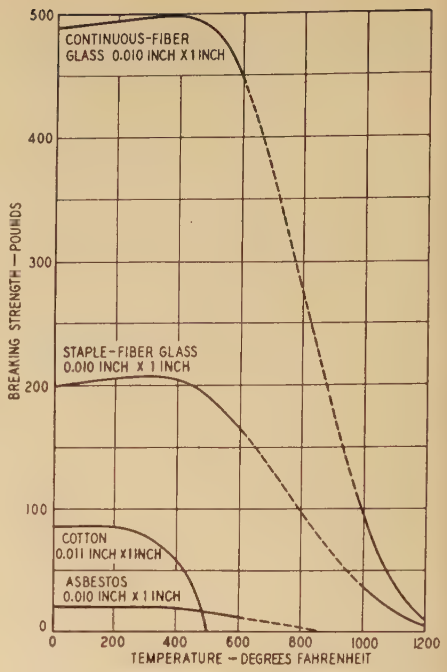

**Figure 1. Effect of heat on tensile strength of electrical tapes**

The effect of heat on the tensile strength of asbestos, cotton, and fiber-glass tapes is shown graphically in figure 1. Each curve represents averages of numerous determinations obtained over a period of a year.

Data below 600 degrees Fahrenheit were obtained by heating the tape in an electric resistance oven for at least 24 hours in each case and then breaking the specimens in a pendulum-type tensile-strength tester, the average of five good breaks being used to determine each point. Above 1,000 degrees Fahrenheit the data were obtained by heating the tape in a small electric furnace and then determining the breaking strength in the same manner. No data were obtained between 600 degrees and 1,000 degrees; hence that portion of the curve is dotted. Throughout this series of tests, the maximum deviations from the mean were +10.5 per cent and −20.5 per cent.

**Table II. Breaking Strength in Pounds of 0.010 Inch by 1 Inch Staple-Fiber Tapes After Subjection to Different Temperature Cycles Simulating Those Which Might Be Encountered by Electrical Equipment in Operation**

| | Original Conditions | 400 Deg F for 30 Minutes | 400 Deg F for 30 Minutes Each Day for 10 Consecutive Days | 500 Deg F for 30 Minutes | 500 Deg F for 30 Minutes Each Day for 10 Consecutive Days |
|---|---|---|---|---|---|
| | 234 | 240 | 180 | 180 | 167 |
| | 182 | 187 | 198 | 185 | 157 |
| | 205 | 239 | 195 | 200 | 165 |
| | 213 | 200 | 195 | 190 | 176 |
| | 218 | 229 | 184 | 205 | 166 |
| Average | 210 | 219 | 190 | 194 | 166 |

Table III. Flexing Endurance

Samples 0.010 Inch by 1 Inch by 17 Inches

| | Yellow Varnished Cotton Cloth | Yellow Varnished Glass Cloth |
|---|---|---|
| As received | 2,100 | 2,700 |
| After 280 deg F 24 hours | 12,000 | 72,000 |
| After 350 deg F 2 hours | 4,500 | 80,000 |

Table IV. Dielectric Strength of Standard Unimpregnated Cotton, Asbestos, and Fiber Glass Tapes

All Samples 0.015 Inch by 1 Inch Nominal Except the Cotton Which Was 0.011 Inch by 1 Inch

| | As Received | | | | Washed* | | | |
|---|---|---|---|---|---|---|---|---|
| | Average Thickness (Inch) | Volts Per Mil | | | Average Thickness (Inch) | Volts Per Mil | | |
| | | Maximum | Average | Minimum | | Maximum | Average | Minimum |
| Cotton | 0.0121 | 99.5 | 94.5 | 82.9 | 0.0156 | 92.5 | 88.5 | 86.3 |
| Asbestos | 0.0151 | 66.2 | 58.3 | 45.0 | 0.0201 | 57.8 | 51.2 | 42.9 |
| Continuous-fiber glass | 0.0168 | 98.0 | 94.4 | 92.1 | 0.0135 | 107.2 | 97.3 | 92.5 |
| Staple-fiber glass | 0.0162 | 98.9 | 92.3 | 83.5 | 0.0152 | 102.3 | 99.6 | 95 7 |

NOTE: Tests were made by the short time method at room temperature of approximately 80 degrees Fahrenheit and 65 per cent relative humidity using one-fourth inch diameter brass electrodes and increasing voltage at the rate of 500 volts per second to breakdown. Each value is maximum, average, or minimum of ten readings of breakdown voltage divided by the average of ten readings of thickness.

* Samples were washed by boiling for 15 minutes in water containing 0.5 per cent soap and 0.2 per cent soda ash by weight; then dried in an oven at 225 degrees Fahrenheit for 30 minutes and conditioned at room conditions (approximately 80 degrees Fahrenheit and 65 per cent relative humidity) for at least 96 hours.

These curves show that glass tape is from 2 to 20 times as strong at room temperature as similar tapes made of other commonly used fibrous materials. The strength of glass tape does not diminish appreciably up to 600 degrees Fahrenheit and after 24 hours at 800 degrees Fahrenheit, it still retains half of its original strength.

## Resistance to Abrasion

There is a wide variation of opinion as to what constitutes a proper test for the abrasion resistance of textiles. For this reason no conclusive tests have been made on fiber-glass fabrics. Tests have been made, however, on untreated and on impregnated tapes by sliding a five-pound steel weight (the bearing surface being knurled and on one-half inch radius) back and forth on a one-inch-wide specimen stretched over a steel plate. Revolutions of the reciprocating arm which drove the weight were counted until electrical contact was made between the five-pound weight and the steel plate.

With this method of test, untreated fiber-glass tape appeared to be on a par with equivalent asbestos tape, but weaker than cotton. The samples were not entirely comparable, however, due to the more open weave of the asbestos and the glass. Similar tests on impregnated tapes showed the glass tape to be the strongest of the three.

One or two manufacturers have said that some difficulty has been experienced due to the cutting of glass on sharp edges of metal during coil-winding operations. Others say that with reasonable care on the part of the workmen no difficulty is encountered.

## Flexing Endurance

Insulation for many applications requires a considerable degree of flexibility and at the same time endurance to flexing, both during the treating and impregnating processes and during application on or in the finished equipment.

That glass fibers are spun, twisted, and woven on standard textile machinery into fabrics as thin as 0.002 inch is some indication of their flexibility. Using the test apparatus described below, five samples of standard 0.010-by-1-inch untreated continuous-fiber glass tape broke after an average of 26,500 flexes. Table III shows the number of flexes required to break one-inch-wide samples of 0.010 inch thick commercial yellow, varnished, cotton, and glass cloths after various heat treatments.

In making these tests one end of a sample 17 inches long was attached to a clamp fastened to the rim of a pulley 13 inches in diameter. The other end of the sample was attached to a stationary clamp placed below the pulley clamp so that

Table V. Dielectric Strength of Varnished Fiber-Glass Cloth as Compared With Standard Varnished Cotton Cambric After Short-Time Heat Treatment

| | Average Thickness (Inch) | Volts per Mil | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | As Received | | | After 250 Deg F for Two Hours | | | After 350 Deg F for Two Hours | | | After 450 Deg F for Two Hours | | |
| | | Minimum | Average | Maximum | Minimum | Average | Maximum | Minimum | Average | Maximum | Minimum | Average | Maximum |
| **Yellow Insulating Varnish** | | | | | | | | | | | | | |
| Cotton | 0.0093 | 842 | 915 | 1,038 | 911 | 982 | 1,046 | 928 | 982 | 1,019 | 964 | 1,065 | 1,121 |
| Glass | 0.0100 | 897 | 1,018 | 1,067 | 1,105 | 1,145 | 1,200 | 1,277 | 1,289 | 1,310 | 1,411 | 1,487 | 1,586 |
| **Black Insulating Varnish** | | | | | | | | | | | | | |
| Cotton | 0.0105 | 1,148 | 1,296 | 1,386 | 1,332 | 1,370 | 1,444 | 1,092 | 1,220 | 1,335 | 1,052 | 1,105 | 1,132 |
| Glass | 0.0095 | 1,243 | 1,312 | 1,368 | 1,220 | 1,362 | 1,538 | 1,187 | 1,372 | 1,680 | 1,195 | 1,400 | 1,518 |
| **After Creasing*** | | | | | | | | | | | | | |
| Yellow cotton | 0.0095 | 317 | 590 | 844 | 272 | 422 | 523 | 169 | 403 | 675 | 201 | 440 | 638 |
| Yellow glass | 0.0097 | 524 | 563 | 606 | 481 | 532 | 642 | 548 | 677 | 767 | 541 | 665 | 917 |
| Black cotton | 0.101 | 139 | 519 | 872 | 152 | 538 | 721 | 105 | 122 | 141 | 99 | 121 | 129 |
| Black glass | 0.0096 | 733 | 876 | 984 | 713 | 933 | 1.242 | 170 | 462 | 940 | 156 | 398 | 1,015 |

NOTE: All samples in table V were taken from standard rolls of cloth varnished by a manufacturer of varnished cotton cambric, the same respective varnishes being used on both the cotton and the glass. Nominal thickness of cloth was 0.010 inch but actual average thickness determined with a one-fourth-inch-diameter micrometer are shown for the cloth as received. Each value of dielectric strength is maximum, average, or minimum of ten readings of breakdown voltage divided by the average of ten readings of thickness determined separately for each sample. All tests were made by the short-time method at room conditions of approximately 80 deg Fahrenheit and 65 per cent relative humidity, using standard two-inch-diameter electrodes. Voltage was increased at the rate of 500 volts per second to breakdown.

* Samples were creased by bending double both ways and creasing between thumb and index finger as in creasing paper for tearing. Electrodes were placed directly over the creases.

**Table VI. Dielectric Strength of Fiber-Glass Cloths Impregnated With Various Insulating Varnishes After Heating at 350 Degrees Fahrenheit for 140 Hours**

| Sample number | | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| Impregnant | | Clear air-drying varnish | Clear baking varnish | Clear baking varnish | Alkyd resin varnish | Yellow cambric insulating varnish | Black cambric insulating varnish |
| Average thickness (inch) | | 0.0067 | 0.0107 | 0.0075 | 0.0061 | 0.0076 | 0.0074 |
| Dielectric strength (volts per mil) | Maximum | 1,460 | 1,498 | 1,815 | 1,767 | 1,559 | 1,438 |
| | Average | 1,170 | 1,111 | 1,590 | 1,561 | 1,383 | 1,230 |
| | Minimum | 893 | 608 | 1,194 | 1,437 | 1,190 | 1,008 |

Note: Sample numbers 1, 2, 3, and 4 prepared by hand dipping thoroughly clean 0.004-inch-thick continuous-fiber glass cloth in comparatively thin solutions of varnishes, each one receiving three coats. Samples 5 and 6 were taken from the same rolls of commercially varnished cloth as the samples of table V.

there was one inch of slack when the pulley clamp was at the point of maximum distance from the stationary clamp. The pulley was rotated at a speed of 300 rpm creating a whipping motion causing a constant flexing of the fibers within the tape. Readings were taken of the time required to wear out each sample. Test values are shown only to the nearest hundred flexes.

## Dielectric Strength

The dielectric strength of unimpregnated fiber-glass insulation as it comes from the loom is about the same as that of equivalent cotton textiles, both being determined largely by atmospheric conditions, fiber surface contamination, etc. If the effect of the surface contamination be minimized by thorough washing and drying, the dielectric strength of the glass increases approximately 3 per cent, but that of the cotton decreases about 6 per cent and asbestos about 12 per cent, due to the absorption of moisture and the attendant swelling.

The results of tests on three types of unimpregnated tape, asbestos, cotton, and glass, both "from-the-loom" and washed, are shown in table IV.

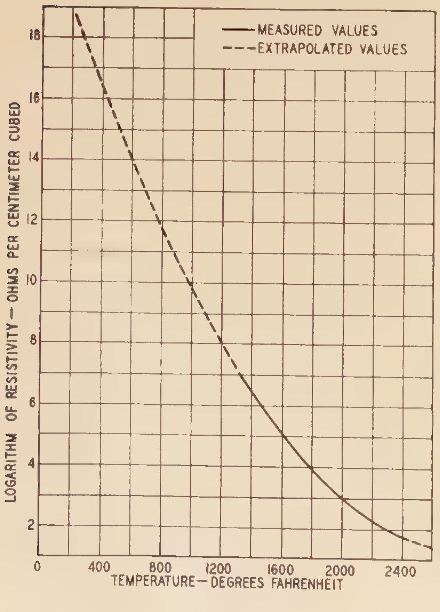

**Figure 2.** Volume resistivity of alkali-free glass

Table V shows a direct comparison between the dielectric strengths of commercially varnished cotton cambric and varnished fiber-glass cloth after various short-time heat treatments, the varnishes used being the same for both cotton and glass cloth.

It will be noted that in the case of the black varnish, there is little difference between the cotton and the fiber-glass averages after subjection to temperatures up to 250 degrees Fahrenheit. But after 350 degrees Fahrenheit and 400 degrees Fahrenheit for two hours, the averages for the glass are 11 per cent and 27 per cent higher than those for cotton.

The differences in the case of the yellow varnish (which, of course, has greater heat resistance than black varnish) are more pronounced, varying from 11 per cent with no heat treatment to 40 per cent after heating at 450 degrees Fahrenheit for two hours.

Perhaps the most plausible explanation for these results is that the heat treatment was sufficient to cause an appreciable amount of carbonization of the cotton fibers and yet not severe enough adversely to affect the dielectric strength of the varnish or the glass fibers. In fact the values in table V again demonstrate the already accepted fact that heat treatment of this nature definitely improves the dielectric strength of most insulating varnishes.

Table VI is included here to show some of the results obtained in efforts to determine what dielectric strengths could be expected of fiber-glass cloths impregnated with heat resistant varnishes after subjection to sustained high temperatures. Samples numbers 1, 2, 3, and 4 were prepared by hand-dipping 0.004-inch-thick continuous-fiber glass cloth (previously washed) into thin solutions of the varnishes, each being given three coats. Samples number 5 and 6 were varnished commercially (from same rolls as samples in table V).

In hand application ordinary varnished tapes are often stretched sufficiently to exceed the elastic limit of the varnish thereby impairing their insulating value. As glass fibers do not stretch, the varnish on glass tapes is not impaired in this manner.

It is not intended that these values be considered as directly comparative for the reasons that the thickness of the finished samples varies considerably and that two of the samples were varnished on standard varnishing towers and the rest hand-dipped. It is significant, however, that for five of the six samples the values of minimum dielectric strength are well above the accepted specifications for varnished cotton cambric and the minimum of one sample is over 1,400 volts per mil.

All samples were heated in a thermostatically controlled electric resistance

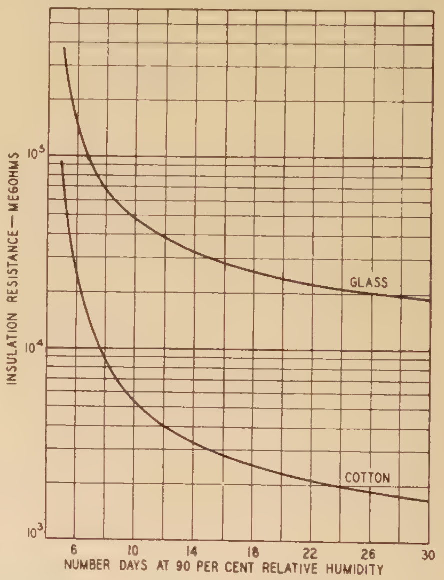

**Figure 3.** Samples of 0.010 inch by 1 inch by 1 inch black varnished cloth after heating at 350 degrees Fahrenheit for two hours

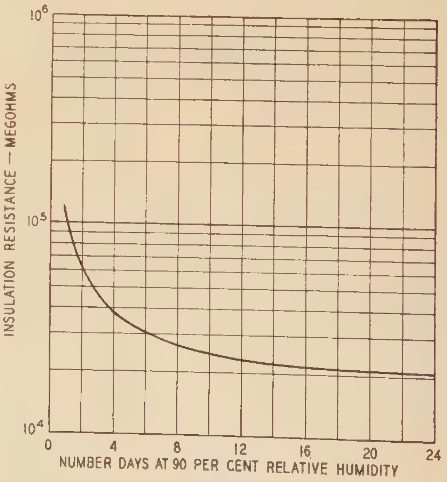

**Figure 4.** Glass tape 0.010 inch by 1 inch by 1 inch coated with water-soluble bakelite

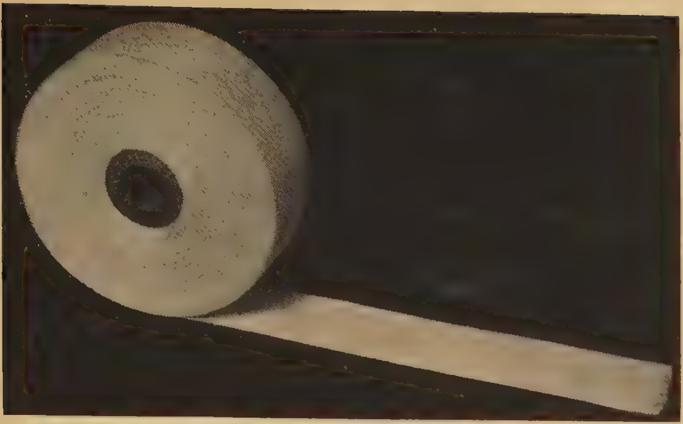

**Figure 5 (above).** Standard roll of continuous-fiber tape 0.003 inch by ¾ inch

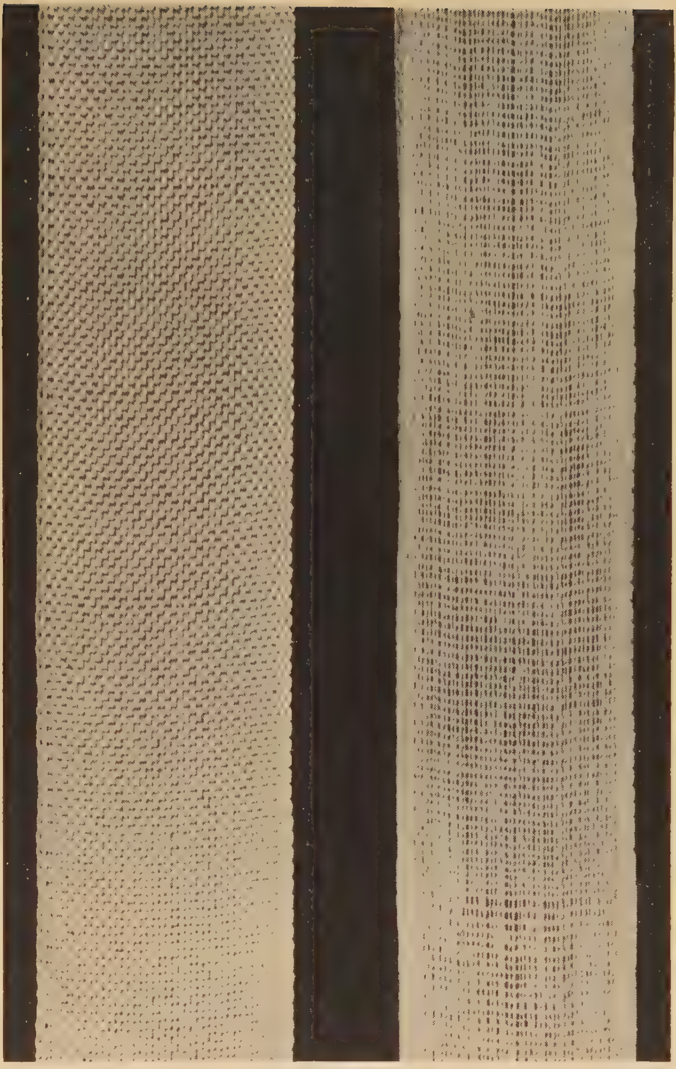

**Figure 6 (left).** 0.003 inch by ¾ inch standard continuous glass tape; right—0.007 inch by ¾ inch standard cotton tape

oven at 350 degrees Fahrenheit for 140 hours and tested for dielectric strength at room condition of approximately 80 degrees Fahrenheit and 65 per cent relative humidity within two hours after being removed from the oven.

It is well known that varnished textiles tend to become brittle at high temperatures and are therefore subject to cracking and subsequent dielectric failure. Glass textiles are no exception to this rule, but table V shows that the effect of the brittleness of the impregnant is not so pronounced on glass fibers as on the weaker and less-heat-resistant cotton textiles.

One test often used as a criterion for flexibility of a piece of varnished cloth is to bend it around a one-eighth-inch-diameter rod. If no cracks are observed in the varnish, the cloth is considered to be sufficiently flexible. Table V shows the results of a more severe test for the weakening or cracking of the varnish on cotton and fiber-glass cloths after various heat treatments. After the heat treatment, the samples were creased by bending double both ways and creasing between thumb and index finger as creasing paper for tearing. The two-inch-diameter electrode was placed directly over the crease in making dielectric strength tests.

It will be noted by comparing values in the third column in table V that creasing causes the "as received" yellow cotton to lose 62 per cent of its original minimum value, yellow fiber glass loses 41 per cent, black cotton 88 per cent, black glass 41 per cent. After 350 degrees Fahrenheit for two hours the percentage loss for yellow cotton is 80 per cent as against 39 per cent for the yellow glass cloth.

## Insulation Resistance

### A. Volume Resistance

The volume resistivity of the alkali-free glass used for electrical insulation is much greater than that of the glasses listed in the International Critical Tables. This is attributed to the absence of soda and potash which have been found by Littleton and Morey[1] to decrease the volume resistivity of solid glass considerably. Figure 2 shows the volume resistivity of electrical-insulation glass at different temperatures. Six determinations between 1,360 degrees Fahrenheit and 2,460 degrees Fahrenheit were made in essentially the same manner as was used by Kohlenrausch[2] in determining the conductivity of salt solutions. The electrodes used were made of platinum and were calibrated with a number of standard solutions having approximately the same range of resistivity as molten glass. A 1,000-cycle source of power was used and resistance measurements made by means of a General Radio type 650*A* impedance bridge.

### B. Surface Resistance

Because of the high ratio of exposed surface area to the total weight of fiber glass (about 1,500 square feet per pound) measured values of insulation resistance at normal temperatures may be considered as purely surface resistance without appreciable error. This surface resistance is affected not only by the glass constituents, but to a very marked degree by the relative humidity of the atmosphere. This is illustrated in table VII which shows the insulation resistance

**Table VII. Insulation Resistance in Megohms of Standard Unimpregnated Tapes One Inch Square After 72 Hours at 100 Degrees Fahrenheit and 90 Per Cent and 75 Per Cent Relative Humidity**

| | "From the Loom" | | Washed | |
|---|---|---|---|---|
| | 90 Per Cent Relative Humidity | 75 Per Cent Relative Humidity | 90 Per Cent Relative Humidity | 75 Per Cent Relative Humidity |
| 0.015 by 1 inch asbestos | 0.57 | 1.08 | 1.5 | 5.5 |
| 0.011 by 1 inch cotton | 1.03 | 35 | 30.5 | 380 |
| 0.015 by 1 inch glass | 12.4 | 200 | 1,400 | 30,100 |

**Figure 7.** View in twisting mill showing the fabrication of continuous-fiber glass yarns

across one-inch-square samples of standard unimpregnated tapes both from the loom and washed (boiled 15 minutes in 0.5 per cent solution of soap in distilled water), after being held at 100 degrees Fahrenheit and the indicated relative humidities for 72 hours.

Figure 3 shows the variation in insulation resistance of one-inch-square samples of black varnished cotton and glass cloth over a period of 30 days at 100 degrees Fahrenheit and 90 per cent relative humidity.

When fiber-glass tape is coated (not impregnated) with a solution of a water-soluble bakelite and then dried, the insulation resistance becomes higher than that of the untreated tape. Figure 4 shows the variation in insulation resistance at 90 per cent relative humidity of a sample prepared in this manner. The solution of bakelite was $12^{1}/_{2}$ per cent solids by weight and the sample was dried for 90 minutes at 250 degrees Fahrenheit.

All insulation resistance determinations were made with a Leeds and Northrup insulation-resistance test set of the guard-circuit type consisting of high-sensitivity galvanometer, Aryton shunt, and lamp and scale device. The electrodes were brass clamps supported in a bakelite board on two-inch centers one being guarded by a brass ring. The bakelite board served as the cover for a $4^{1}/_{2}$-inch-diameter glass jar, in the bottom of which was a saturated solution of the proper salt for the desired humidity. ($KNO_3$ was used for 90 per cent relative humidity and NaCl for 75 per cent relative humidity at 100 degrees Fahrenheit.) The guard circuit was complete from electrode to galvanometer. Source of current was five 45-volt radio *B* batteries in series. Readings were taken one minute after the specimen circuit was closed.

The results obtained by R. E. Ferris and G. L. Moses of the Westinghouse Electric and Manufacturing Company on the insulation resistance of a cotton-insulated coil and an asbestos insulated coil at 99 per cent relative humidity show essentially the same trend over a period of 14 days as is seen in figure 3 although the asbestos failed to ground on the 13th day.

## Hygroscopicity

One of the most difficult problems to solve in connection with electrical insulation is that of failure due to the absorption of moisture. In some cases this is the primary concern of design and maintenance engineers. Glass insulation, being nonhygroscopic, is proving valuable under extreme conditions of high relative humidity coupled with intermittent high overload temperatures. Notable examples have come from the bituminous coal fields of western Pennsylvania. One company, which operates a large number of mining locomotives, reports that the average life of motor windings operating under the worst conditions has been lengthened considerably by the use of fiber-glass-insulated coils.

Reference to table IV will show that after washing and thorough drying, the average thickness of cotton and asbestos tapes had increased. This does not occur in glass tapes.

Glass insulation is available in the same forms and sizes as are other fabrics, the following being stocked:

*Tape.* Continuous fiber 0.005 inch by $^{1}/_{4}$ inch to 0.015 inch by $1^{1}/_{2}$ inches; staple fiber 0.010 inch by $^{1}/_{4}$ inch to 0.025 inch by $1^{1}/_{2}$ inches.

*Braided Sleeving.* Made from continuous-fiber yarns in standard inside diameters of $^{1}/_{16}$ inch, $^{1}/_{8}$ inch, $2^{1}/_{4}$ inches with wall thickness of 0.015 inch.

*Varnished Cloth and Tape.* Black and yellow varnished cloth and tape are available in the same widths and thicknesses as varnished cotton cambric.

*Glass Insulated Wire.* All sizes of round and square wire are being covered successfully with glass yarn, different thicknesses being used to obtain the same over-all diameters as standard wire insulated with asbestos, cotton, paper, and silk.

*Combination Mica and Glass.* A number of mica and glass combinations are being used for transformer coil, and armature coil, and slot insulation. This combination is a class-*C* insulation except for a small amount of organic binder.

## Summary

In summing up the characteristics of fiber glass those which make it valuable for electrical insulation are:

1. Noninflammable and highly heat resistant. The operable temperature is limited only by the impregnant used, and there is a very definite temperature range between the operable temperature of organic fabrics and that of heat-resistant impregnants where glass is unique.
2. Exceptionally high tensile strength.
3. Nonhygroscopic.
4. Resists attack by moisture, acids, oils, and corrosive vapors.
5. Good thermal conductivity.
6. Excellent dielectric strength when impregnated.
7. High insulation resistance.

## References

1. ELECTRICAL PROPERTIES OF GLASS, Littleton and Morey, John Wiley & Sons.

2. CONDUCTIVITY OF SOLUTIONS, Cecil W. Davies.

# Discussion

**L. E. Fogg** and **R. B. Power** (Kennecott Wire and Cable Company, Phillipsdale, R. I.): Mr. Atkinson has outlined the properties of fiber glass which promise to make it an important factor in the field of electrical insulation. These properties are such that frequently fiber glass may be used advantageously in place of other insulations and it may provide a satisfactory solution for a number of difficult insulation problems. There are, however, a few comments that should be made with regard to the use of this material.

There is one point in connection with the mechanical strength of the material which would bear some clarification. The results of the flexing endurance tests as reported in table III show that a certain amount of heat treatment apparently toughens the insulation, and might make such treatment a desirable part of the preparation of the material. The cause for this improvement is not readily apparent, and should have some explanation by the author.

In table IV giving dielectric strength comparisons, Mr. Atkinson has indicated slight improvements of the glass, and slight loss for the other insulations through washing. For thin insulations there is always an increase in the dielectric strength as the thickness of the material is decreased. It seems probable that this factor is more responsible for the slight increases and decreases noted above, than any other change in the insulations. The cotton and asbestos fabrics, showing increases in thickness with washing, show a corresponding decrease in dielectric strength, while the glass, with a decrease in thickness shows an improved dielectric strength.

The lubricating oil applied to the fiber during manufacture may have some slight effect on the dielectric strength of the glass tape. However, this oil may be very detrimental if thermal and electrical conditions of insulation use are such as to make dielectric loss an important factor.

It is worth pointing out that the dielectric strength of asbestos may vary greatly from the values shown in the same table, depending on the method of preparing the asbestos tape. Some comparative dielectric-strength measurements were made recently at our laboratory on fiber glass and asbestos tape in which the asbestos had been fabricated on a cotton backing. Although the fiber glass gave results almost identical with those of Mr. Atkinson, this asbestos tape showed about 60 per cent higher dielectric strength than did the samples he reported.

It is unfortunate that in most applications of fiber glass as insulation it is necessary to use some bonding, saturating, or coating material in conjunction with the glass. Some tests which we have made recently show that if fiber glass alone could be used it would retain some insulating properties at temperatures approaching its softening point. Such temperatures cannot be attained in practical applications, however, and in most cases the maximum operating temperatures for fiber-glass-insulated equipment will be limited to a moderate value by associated insulating materials. These facts should be kept in mind when considering fiber-glass insulation for high-temperature operation.

Unquestionably, glass as a fibrous insulating material will eventually find its proper place among other similar materials. The information presented by Mr. Atkinson should indicate some places where its use would be definitely practicable.

**R. W. Wieseman** (General Electric Company, Schenectady, N. Y.): For rotating-machine windings a large variety of class *A* organic insulating materials are available. These materials are inexpensive, easy to apply, and they have been used successfully for many years. As the machine voltage, speed, and size increased inorganic materials were introduced to increase the life of the windings by resisting the action of mechanical stresses, corona, and elevated temperatures.

Unfortunately only two inorganic materials were suitable for rotating-machine windings up to the present time, namely, asbestos and mica in built-up form. Mica is an excellent high-voltage high-temperature moisture-resisting insulator if properly filled and bonded. It is limited mechanically, however, by the characteristics of its bonding medium. Some asbestos textiles contain as much as 20 per cent cotton. It is well known that asbestos absorbs moisture readily and it contains natural ferrous particles and conducting salts which must be removed if it is to be used in the region of high-voltage stresses. Asbestos, therefore, is usually confined to low voltages where mechanical strength is required at elevated temperatures and as an armor for high-voltage mica insulation. It is apparent that present inorganic materials, although satisfactory, are not ideal for rotating-machine insulation.

The introduction of glass-fiber insulation is welcomed by those interested in rotating machines. When properly filled with a suitable varnish or compound, glass fiber is a good class *B* insulating material. Up to the present time glass fiber alone is not a competitor to mica for high-voltage windings. Glass fiber, however, should be beneficial in many respects. First, it can replace cotton which is used for structural purposes in class *B* insulation, and thereby produce better mechanical and thermal properties. Second, it can replace asbestos with an improvement in uniformity, mechanical strength, and voltage strength. Third, it can partially replace mica on low- and medium-voltage coils with an improvement in mechanical strength. It also can be used as an armor or outside covering for high-voltage mica-insulated coils.

D-c and a-c machines have been built with glass-insulated wire in both the armature and field windings. Coils of many kinds have been insulated with glass tape and mica in several combinations. The end connections of armature windings have been insulated with treated glass tape and combinations of glass and mica tape. A 1,500-kw 600-volt d-c machine was insulated entirely with mica and glass. None of its six windings contains cotton or asbestos in any form. Insofar as machine temperatures are concerned the thermal limitation of the windings of this machine is governed only by the insulating varnish and filling compounds used in building the insulation structure.

Glass fiber in various forms can be used to advantage in rotating-machine insulation. The extent to which it will replace present materials will depend somewhat on technical and economic conditions because its feasibility has been established.

**E. F. Dissmeyer** (The Commonwealth and Southern Corporation, Jackson, Mich.): Mr. Atkinson's paper provides a very complete comparison of the characteristics of cotton and glass when used as insulating materials. In the future, glass will undoubtedly provide an answer to many of our insulation application problems.

A number of other characteristics of glass insulation would, of course, be of interest. Certain of these are:

1. How does the dielectric strength of glass under impulse conditions compare with that of other insulating materials?

2. In transformer applications, a majority of the dielectric strength between turns is provided by the oil-saturated paper covering on the conductors. Would a glass reinforcement over the paper provide better dielectric strength?

3. One of the problems which confronts the manufacturer is that of getting varnish into the interior of coils. With cotton insulations, the varnish can be "wicked" in only a short distance. How do the "wicking" properties of glass compare with those of cotton?

**E. L. Lotz** (New Jersey Wood Finishing Company, Woodbridge, N. J.): The information on fiber glass presented by Mr. Atkinson is extremely valuable and timely in view of the newness of the product and of the widespread interest in this type of insulation and of the possibility of the increased temperature ratings of electrical equipment and allied insulation.

With the tremendous advances made in the manufacture of insulating varnishes and impregnating compounds in the last few years, it has become more and more apparent that the limiting factor in the operation of insulation at high temperatures is not the varnish or impregnating compound, but the carrier on which they are used. Cotton when impregnated or coated and subjected to high temperatures (125 degrees centigrade) fails only in a mechanical sense, that is, it fails in so far as tensile and tearing strength are concerned but does not fail electrically as the dielectric strength of the varnish or compound will, if anything, be higher after the heat treatment. The use of fiber glass as the carrier should insure both good electrical and mechanical properties even after exposure to high temperatures for long periods of time.

The dielectric strength of cotton and glass impregnated with the same varnish is substantially the same as is also the case for the two in the unvarnished state. This means that the dielectric strength is determined almost entirely by the type of varnish used, as is clearly shown in table VI of the paper.

The curves in figure 3 are very interesting and would tend to show that varnished glass cloth is considerably better than varnished cotton cloth under conditions of high humidity. I have tested both glass and cotton for resistance to moisture and have found that varnished cotton compares very favorably with varnished glass in respect to power factor and dielectric strength. The experiment consisted of vacuum-drying samples of black varnished cotton and fiber glass at

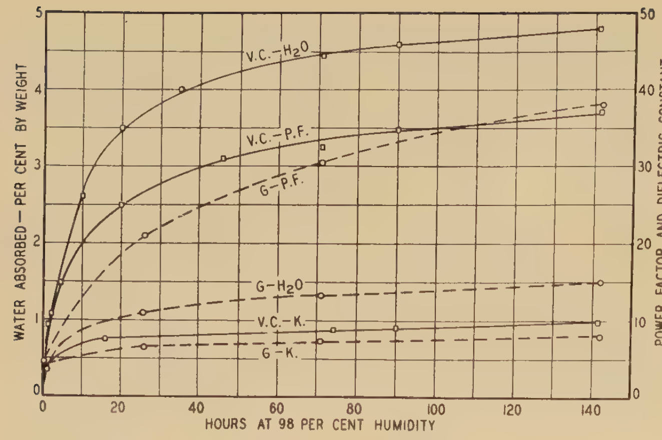

**Figure 1. Water absorption of varnished glass and cotton**

105 degrees centigrade for six hours under a vacuum of 0.1 millimeter and then exposing the samples to 98 per cent relative humidity and determining the amount of water absorbed, the power factor, and dielectric constant. The result of this experiment is shown in figure 1 of this discussion. The curves are plotted against hours of exposure and show that even though the varnished glass absorbed much less water, the resultant power factor was just as high as the varnished cotton. The curve designated *V.C.-P.F.* means the power factor of the varnished cotton, whereas, *G-P.F.* is the similar curve for varnished glass. In both cases, there was an initial rapid increase in water absorbed, power factor, and dielectric constant in the first ten hours.

In order to compare the dielectric strength after exposure to moisture, samples which had been vacuum dried as above were immersed in water at 24 degrees centigrade for 24 and 42 hours and the amount of water absorbed and decrease in dielectric strength measured. The dielectric strength was measured using one-fourth inch electrodes and the short time ASTM method of test. The results are shown in table I of this discussion. After 24 hours, the varnished glass had absorbed 0.77 per cent water by weight and had a reduction in dielectric strength of 46.2. Varnished cotton absorbed 3.2 per cent water by weight, but the reduction in dielectric strength was only 30.85. After 42 hours the glass had absorbed 1.1 per cent water by weight with a reduction in dielectric strength of 59.2 per cent. The varnished cotton absorbed 4.35 per cent water by weight and had a decrease in dielectric strength of 48.5 per cent.

**Table I. Water Absorption-Dielectric Strength**

| Exposure | Water Absorbed (Per Cent by Weight) | Per Cent Reduction in Dielectric Strength |
|---|---|---|
| **Black Fiber Glass** | | |
| 24 hours in water at 24 degrees centigrade | 0.77 | 46.2 |
| 42 hours in water at 24 degrees centigrade | 1.1 | 59.2 |
| **Black Cotton Tape** | | |
| 24 hours in water at 24 degrees centigrade | 3.2 | 30.85 |
| 42 hours in water at 24 degrees centigrade | 4.35 | 48.5 |

In the above experiments, the same varnish was used on both the cotton and glass and it is reasonable to assume that in each case the varnish itself would be affected to the same degree so that the difference in the performance of the two must be directly dependent on the carrier. Since glass is nonhygroscopic the mechanism of the water absorption is probably of the nature of a surface layer on the glass fibers. In the case of cotton most of the water is taken up by a wick action and since the carrier itself does not contribute anything to the dielectric strength, the presence of the large amount of water in the cotton does not show up in the dielectric-strength measurements.

**Lloyd E. Miller** (Reliance Electric and Engineering Company, Cleveland, Ohio): Mr. Atkinson's paper is so complete as to detail, that it leaves practically nothing to the imagination and very little concerning the physical characteristics given in the paper, to discuss.

There is, however, a feature that might very well be discussed regarding the commercial usage of this material. The high temperature to which fiber glass can be subjected has been stressed in this paper and in previous papers and talks. It might be said to have been overstressed. It has been stressed so much that it has been ill advisedly seized on by many as proof that with this material the industry is now ready to double the temperature at which electrical machinery can be operated.

The fact that impregnants must be used in conjunction with fibrous insulation, and the fact that all satisfactory impregnants to date are entirely, or in part, of organic material, and are, therefore, the limiting factor in such combination, seems to have been neglected. It is noted that Mr. Atkinson mentions this in his paper, but it seems that it should be more strongly emphasized than in the past. This fact should serve as a spur to the varnish manufacturers.

It does seem that the electrical industry might profitably consider higher temperatures than are now sanctioned, but extreme changes due to new materials should be approached with caution.

It should be borne in mind that the ability of fibrous insulation to withstand high temperatures is not of itself sufficient to justify such changes. Fire hazard must be considered, as must also strains and movements set up by expansion and contraction.

There is no doubt that the new fibrous glass has given the electrical industry a substantially improved insulating material. It can be accepted as a fact that its heat-resisting properties are considerably above those which can be used by the industry at the present time. It would, therefore, seem that efforts of the manufacturers should be along the line of making the product easier to use and apply.

**Graham Lee Moses** (nonmember; Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.): Mr. Atkinson and his colleagues in the Owens-Corning Fiberglas Corporation have undoubtedly made a very significant contribution to the insulation art. Insulation engineers have long felt that existing class *B* insulating materials had definite limitations and it is hoped that this new material will overcome these defects.

Our experience with fiber glass parallels Mr. Atkinson's on some phases of tests on the fundamental material. However, our experience has largely been in connection with actual commercial machines. We have found that its success depends upon the correct application. It has proved satisfactory on equipment where weight and space requirements necessitate high-temperature operation and the insulation is exposed to high humidity conditions. Our experience in the application of glass insulation to transportation apparatus is detailed in an article by Mr. Ferris and myself which appeared in the December 1938 issue of Electrical Engineering.

Our practical and design experience with glass insulation on commercial apparatus covers a period of nearly two years involving over 50 types of motors and generators and several hundred units. It has also been used on many types of control.

Fiber-glass insulation has its share of desirable characteristics and naturally has its limitations. It should not be substituted wholesale for any existing insulating medium but should be applied with care and consideration only where it is required and its use is economically justified. Applications should be avoided which bring out or emphasize its limitations or weaknesses.

Glass insulation by virtue of its excellent tensile strength under high temperature conditions lends itself to being used for binding class *B* coils and holding other forms of insulation in place. It makes an excellent finishing tape producing the desired strength with long life at high temperatures and a fine glossy finish when properly treated. The excellent tensile strength permits the use of thinner class *B* tapes thereby obtaining improved space factor.

Because it is a woven material its inherent (untreated) dielectric strength is only comparable to that of similar conventional materials. When treated it takes on the characteristics of the impregnant film as do other woven materials. In our opinion it should not be used for the main ground insulation on high-temperature class *B* apparatus. This material is of course not to be considered to replace mica for ground insulation.

One of the present limitations of glass insulation is its relatively low resistance to abrasion when the fibers are not lubricated or supported by impregnation. In tape form the fibers are lubricated by an oil film applied during manufacture. In the apparatus this must be supplemented by varnish or other impregnant. When this lubricant or impregnant is eliminated or its qualities destroyed, vibration is apt to cause abrasive destruction. This very definite limitation must be faced by engineers applying this material.

Another limitation is the relatively low shear strength of the glass fibers. This is an exhibition of the brittleness which has long been associated with glass. To avoid this, apparatus should be designed to prevent exposing glass insulation to sharp corners or edges.

The smooth, silky appearance produces another handicap as it permits the warp to slip on the weft, unless a very close weave is used. This tendency can be minimized by pretreating the tape in varnish and only partially curing before applying the tape.

The next logical step in the development of high-temperature insulation is the production of a high-temperature impregnant properly to lubricate or support glass insulation and give it high dielectric strength at elevated temperatures. In most of the previous points discussed the impregnant is an important factor. The importance of this cannot be overemphasized and the development of fiber-glass insulation has in effect "passed the ball" to the impregnant manufacturers.

In our search for improved insulation to operate at elevated temperatures it must be remembered that as insulation improves it ceases to become the determining factor. Already there are important considerations requiring the operation of some classes of machinery at temperatures below that now permissible for insulation.

One interesting and spectacular experiment which we made, was to operate glass-insulated magnet coils at temperatures around 575 degrees centigrade (1,067 degrees fahrenheit). Some of these operated several hours without failure even though the impregnant was completely destroyed. Naturally, life at this temperature is limited and there was no intent to operate apparatus at such temperatures but it was merely done to demonstrate the reliability under extreme conditions due to failure elsewhere in the control equipment.

Briefly glass insulation is an important addition to our family of insulating materials. It is not a panacea nor a cure-all. In our opinion it should be applied judiciously with full appreciation of the limitations as well as the important advantages. Westinghouse engineers, in the early stages of this development, recognized the possibilities of fibrous glass insulation and recommended the use of the continuous-filament type.

**T. R. Walters** (General Electric Company, Pittsfield, Mass.): The data presented in this paper add considerable to our understanding of this new and very interesting insulating material. The point is well brought out that in the field of varnished fabrics the fabric base is the weaker part of the structure and consequently, replacing the organic with an inorganic fabric has a very beneficial effect on the heat resistance of this class of material.

There are several other points which I would like to bring up. One is that while the data show definitely that fiber glass will successfully withstand a much higher temperature than either cotton or asbestos before losing its tensile strength, these tests were all on a short-time basis. It would be interesting to know just how high a temperature these new fibers will stand successfully for very long periods of time. Also, as a matter of record, were the tensile tests reported taken at the temperatures shown on figure 1, or were they taken at room temperature after aging at the indicated temperatures?

In the section concerning dielectric strength, it is stated that "The dielectric strength of unimpregnated fiber-glass insulation as it comes from the loom is about the same as that of equivalent cotton textiles." This being so, I would be interested in the author's theory as to why fiber-glass insulation produces higher dielectric strengths than cotton when the same varnishes are used. A possible explanation is given for the results obtained after heat treatment but not for the higher results obtained on the samples before aging.

In another part of this same section, a statement is made that "In hand application ordinary varnished tapes are often stretched sufficiently to exceed the elastic limit of the varnish, thereby impairing their insulating value," followed by the statement that since glass fibers do not stretch, the varnish on glass tapes is not impaired. Varnished cotton cloth can also be made which will not stretch. Quite often, however, due to the nature of the surface to which the tape is being applied, it is necessary to use tape which will stretch. The decrease in dielectric strength in this instance, is small for the amount of stretch usually required for satisfactory taping.

**Wm. A. Del Mar** (Habirshaw Cable and Wire Corporation, Yonkers, N. Y.): Fiber glass, from the point of view of the cable designer, is not so much an insulating material as a vehicle or filling for such insulating materials as wax, varnish, or lacquer. In this respect it may be regarded as a competitor of cotton, dry paper, and asbestos. The characteristics of fiber-glass insulation, such as dielectric strength, power factor, and ability to resist heat, cold, or moisture, are essentially those of the associated wax, varnish, or lacquer. Fiber glass gives body and strength to these materials, enabling them to be applied in thicker layers. Its advantages over other fibers are that it does not impair the useful characteristics of the wax, varnish, or lacquer with which it is associated. From this it would appear that the title of this paper is misleading as fiber glass is merely an inorganic vehicle for air or organic insulation.

Fiber glass has a definite value for certain classes of wire such as magnet wire, fixture wire, and small motor leads but, so far, it has not made much headway for the larger types of cables.

Fiber glass is a valuable braid material as it does not decay, burn, or become waterlogged. Here, again, its characteristics are limited by the organic filler which must be used. It is more likely that its application to power cables for some time to come will be along this line rather than for the insulation itself. The present high cost of the fiber glass, as compared with other braid materials, limits its use in large cables to services where other available materials show abnormally rapid deterioration.

Varnished glass cloth insulation, as now made, does not stand heat (96 hours at 125 degrees centigrade) as well as heat-resisting varnished cambric made with the same varnish. It becomes more brittle than the cotton base material. It is to be hoped that this material will be developed to the degree of heat resistance that seems to be inherent in the component materials.

**K. N. Mathes** (General Electric Company, Schenectady, N. Y.): Mr. Atkinson's paper constitutes an excellent survey of the properties of glass fiber insulation. From the standpoint of the manufacturer of electric apparatus the properties and service life in built-up form are of primary importance. Service trials and laboratory tests have established that the electrical and particularly the physical properties of glass fiber insulation depend largely upon the nature and thoroughness of the compound or varnish treatment.

Untreated glass fibers are extremely sensitive to nicking, and unless protected can even cut and destroy each other under conditions of abrasion and vibration. For this reason a film of oil or sizing is applied to the fibers to protect them in the textile operation and allow their use as yarn or fabric. The sizing used at present is somewhat corrosive to copper, hygroscopic, and, in addition, is not truly compatible with most insulating varnishes. Because of the nature of the sizing and the high density in the case of the continuous-filament yarn, it is difficult to secure complete varnish or compound penetration. Although glass is not hygroscopic in the sense that the solid fibers can absorb water, moisture can be picked up in the following ways:

1. As an adsorbed film upon the glass surface.
2. By adsorption in the sizing.
3. By capillarity between fibers or threads.
4. By capillarity between fibers and surrounding varnish which may not satisfactorily wet the fiber.

As a result the moisture resistance of glass fiber as measured by the electrical properties in many cases is only comparable to cotton.

When used as major insulation, the glass fabric serves merely as a matrix to carry the insulating varnish. The extent of the deterioration of the varnish over long periods of time is extremely important. The most characteristic effect is the slow embrittlement and tendency toward cracking which may seriously impair the dielectric strength. In contrast, the overlapping flakes of pasted mica depend upon varnish only as a binder. In addition, since all organic varnishes deteriorate under the action of corona, the varnished glass fabric cannot be considered as a substitute for mica in high-voltage applications.

This discussion emphasizes limitations and precautions which are important to recognize since glass fiber is assuming so rapidly an important place in the field of electrical insulation. Glass insulation has found use in many types of electric apparatus, and will find increased use with further development, and as service data more firmly establish the advantageous properties. In comparison with other types of insulation, in many cases economic consideration may be the deciding factor for use.

**H. C. Louis** (Consolidated Gas, Electric Light and Power Company of Baltimore, Md.): The data in the paper giving the results of the elaborate tests on fiber-glass insulation show this material to have some very desirable and superior characteristics and to open up some very attractive possibilities. The development of this insulating material marks a definite step forward in the progress of insulation development.

Numerous mechanical tests were made as described in the paper, but we wish to stress the importance of giving full consideration to the effect of fatigue effects from vibration. The possibility of deterioration or even pulverization of such material due to this effect in extended service should not be minimized. Operating experience shows numerous troubles in materials to be traceable to vibration fatigue, and possibilities of anticipating and preventing this call for the very best efforts and attention in investigations of the material under consideration.

**Herman Halperin** (Commonwealth Edison Company, Chicago, Ill.): The utilities are, of course, gratified to learn again that the manufacturers are investigating the new kinds of insulation as they are brought forth. Obviously, when these insulations are suitably developed by themselves or as incorporated in apparatus, many utilities will be glad to use them when they become attractive commercially as well as technically.

Referring to the newer insulation, that is, glass, it would be of interest to learn what developments have been made with other types of binders than the varnish and bakelite mentioned by the author. This question, of course, is raised in connection with frequent or continuous operation of glass insulation in apparatus at such temperatures as 150 or 175 degrees centigrade.

**F. W. Atkinson:** L. E. Fogg, R. B. Power, and Lloyd E. Miller refer to the fact that the operable temperatures for glass insulation in most applications must be limited by the impregnant used. Mr. Miller advises caution in design and rating changes in the direction of higher temperature operation, and Herman Halperin raises the question as to impregnants which may be capable of withstanding temperatures such as 150 degrees centigrade or 175 degrees centigrade.

The author fully realizes the necessity for caution in raising the temperature ratings of electrical apparatus in general and that many other considerations make it impossible to operate at temperatures even approaching those which glass will stand. However, as E. L. Lotz and Graham Lee Moses have pointed out in their discussion, as far as the insulation is concerned, the limiting factor with impregnated glass is the impregnant, whereas with class *A* insulations, it is the fabric. Our tests of numerous varnishes on glass and cotton fabrics definitely show that the better heat-resistant varnishes will stand temperatures considerably higher than those which cause cotton to lose practically all of its mechanical strength. Our experience with the relative heat resistance of varnished glass cloth and varnished cotton cambric does not parallel that of Wm. A. Del Mar. Of three different samples of yellow varnished cotton cambric held at 125 degrees centigrade for 168 hours, only one could be bent 180 degrees around a one-eighth-inch-diameter mandrel without cracking. All of the six samples of yellow varnished glass cloth (each varnished by a different company) withstood this test. A few of the better commercial varnishes (applied to glass cloth) have been found to pass this test after a week at 175 degrees centigrade. One experimental impregnant, partly organic, retained remarkable flexibility after 120 hours at 200 degrees centigrade and its minimum dielectric strength was over 1,500 volts per mil (short-time method, one-fourth-inch electrodes, material 0.010 inch thick). It seems reasonable, then, to assume that:

1. The temperature limits of class *A* insulations are determined by the fabric and not by the impregnant.

2. With a fabric that will stand it, varnishes are available which can be used where hot spot temperatures are 150 degrees centigrade or higher.

3. The final word has not been written about heat resistance in impregnants as varnish manufacturers and individuals are making great strides in the improvement of this quality. It is believed that the introduction of glass fabrics into the insulation field has provided further inducement to effort on this particular research problem.

K. N. Mathes and Graham Lee Moses have mentioned the low resistance of untreated glass fabrics to abrasion and shear on sharp edges. This probably is the weakest property of the untreated glass at the present time, although that is not true of treated fabric and it does not seem to be of primary importance. Laboratory tests along this line are not very conclusive so it seems pertinent to refer to the experience encountered by manufacturers in the actual application of "Fiberglas" insulating materials during the three years since their introduction. Few have reported any lasting difficulty due to abrasion and shear and some have indicated as much as 15 per cent saving in labor in the winding of coils. This would hardly be possible if much difficulty were encountered due to nicking and shearing during fabrication. It should be pointed out further that continuous research is definitely minimizing this weakness.

Mr. Mathes mentions the important point of thoroughness of impregnation of treated Fiberglas insulation. This problem, of course, is as applicable to glass as to the other textile insulating materials but no particular difficulty has been found in our laboratory in obtaining thorough impregnation of glass cloth, and the impregnation of wound coils is being carried on by numerous manufacturers with facility and efficiency at least as great as with cotton and asbestos. We have found, however, that some types of varnish wet glass fibers much better than others and this seems to be the high hurdle in accomplishing thorough impregnation of Fiberglas. Heat treatment definitely improves impregnation by strengthening the bond between the varnish and the fibers. We believe this to be, in part, the answer also to the question of Messrs. Fogg and Power regarding the increase in flexing strength of varnished cloth after heat treatment. Another explanation is that the polymerization of thermosetting varnishes adds considerably to their toughness.

T. R. Walters raises the question of variation in tensile strength of Fiberglas with time of exposure to high temperatures. Our experience indicates that there is very little change in the tensile strength of electrical glass (alkali-free) after the first 24 hours.

Cloths made of this type of glass and used for steam-turbine blanket covers retained from 30 per cent to 40 per cent of their original tensile strength after 12 days next to a hot plate maintained at 900 degrees fahrenheit (482 degrees centigrade). This is about the same loss in strength as shown in figure 1. The significant thing, however, is that even after this treatment, the glass cloth is stronger than cotton and asbestos are with no heat treatment.

Messrs. Louis and Moses bring up the point of deterioration due to vibration. We know definitely that if this is an inherent weakness in Fiberglas insulation, it can be proved only after a longer period of time than Fiberglas-insulated apparatus has been in operation; for as far as is known, no failures have been attributable to vibration.

Unfortunately we have at the present time no data to compare directly with the interesting curves presented by E. L. Lotz. However, we have measured the 60-cycle power factor of a number of different samples of varnished cotton and varnished glass cloth at room conditions, and have found no cotton sample whose power factor was lower than 13 per cent nor any glass sample whose power factor was higher than 7 per cent.

So far as we know, no impulse tests, as Mr. Dissmeyer has suggested, have been made. As far as the reinforcement of the dielectric strength of the paper insulation in transformers is concerned, untreated glass could offer little; but varnished glass should provide much greater dielectric strength and resistance to the effects of corona. With reference to the "wicking" of varnish in glass-covered coils, there seems to be no difficulty. In fact, although coil manufacturers are naturally loath to disseminate such information, there is reason to believe that some of them consider that a fewer number of dips are necessary for some types of glass-insulated coils than for other types of insulation.

# Temperature Limits and Characteristics of Mica as Used in Conjunction With Class "B" Insulation

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THE TYPE of class *B* insulation referred to in this paper is primarily intended for small and medium sizes of general purpose motors, generators, and associated equipment.

Of the many different varieties of micas found in the world's mineral deposits, only two are used for electrical insulation, namely, muscovite and phlogopite. Commercial sources of supply are found mainly in India, Madagascar, Africa, Brazil, and Canada. The mica-bearing veins are very erratic in their occurrence; in some localities they are found on and near the surface, while in others, they are several hundred feet below the ground. The yield of commercial mica obtained per ton of rock may be as low as one per cent. In general, the area of rough mica slabs varies from approximately 2 square inches to 50 square inches. However, in exceptional cases, pieces are found as large as three feet by four feet. After the extraneous rock and other incrustations are removed from the slab of mica, it is then split into thicknesses of approximately one-eighth inch—commercially termed "blocks." The blocks are further classified for quality and graded for size by experienced native labor. Details regarding the various recognized qualities and gradings may be found in ASTM method *D*-351-37*T*.

Muscovite mica is often referred to as India mica, white mica, ruby, potassium mica, etc. Clear muscovite films have a dielectric strength of approximately 3,000 volts per mil to 900 volts per mil for thicknesses of 0.002 inch to $^{1}/_{16}$ inch respectively at 25 degrees centigrade. For temperatures of 300 degrees centigrade the dielectric strength is roughly equal to 75 per cent of the stated values. The power factor varies from 0.0001 to 0.0008 at 25 degrees centigrade for a frequency range of 60 cycles per second to 1,000 kilocycles per second. The dielectric constant under the same conditions is 6.5 to 8.5.

Phlogopite mica, which is more universally known as amber or silver mica is softer physically than the muscovite micas. Selected grades of phlogopite mica may be operated at temperatures of 800 degrees centigrade to 900 degrees centigrade as compared to 400 degrees centigrade to 500 degrees centigrade for muscovite mica. Its dielectric properties are, however, poorer than the muscovite micas, the dielectric strength being approximately 70 per cent of the values quoted above and the power factor has a rather wide spread of 0.003 to 0.09.

The most important characteristic of mica which permits its wide use as a dielectric is its basal cleavage. Films or splittings as thin as 0.0003 inch may be produced by skilled natives. Specifications of commercial splittings range from 0.0006 to 0.0013 inch in thickness. By using these thin films or splittings, a high degree of flexibility is obtained for such applications as coil wrappers and molding micanite plates.

The physical limitations of the size or area of the natural micas are overcome, to a large extent, by assembling the films into large sheets with the aid of suitable binders. A wide variety of types of "built-up" or Micanite plates and wrappers are obtained by combinations of binders, adhesives, carriers, and heat and pressing operations. The following general classifications of micanite plate and other combinations of mica fall within the AIEE definition of class *B* insulation:

Group I. Hard, rigid sheets for commutator segments, etc., contain a minimum percentage of binder (shellac or Glyptal) which has been polymerized to prevent exuding of the binder and slippage of the mica films when subjected to heat and pressure. Organic-bonded heater plates for resistance elements that are mechanically supported also come within this group.

Group II. Hot molding plates for cylinders, vee rings, slot cells, etc., containing from 10 per cent to 20 per cent of shellac or Glyptal binders which are undercured to facilitate molding and forming operations. Additional heat treatment or curing cycles are required on this type of plate to make it suitable for supporting mechanical loads at elevated temperatures.

Group III. Cold flexible plate for slot, phase, and ground insulation can be formed readily at room temperatures. The binder is essentially composed of nondrying oils, plasticizers, and natural and synthetic resins. It, therefore, should not be used under high mechanical loads where stability is of paramount importance.

Group IV. Composite Insulation. The mica splittings are usually backed with, or sandwiched between, carriers such as capacitor tissue, silk, cotton, cellulose acetate, Fiberglas, asbestos, slot papers, or varnish-coated cloths. The carriers provide sufficient mechanical strength to enable the mica films to be applied directly to the conductors and coils. The binders used in these combinations are comparable to those listed in group III with the addition of asphalts and pitches.

The percentage of mica by weight in the composite insulations varies over wide limits, depending upon the materials used. For the thinner carriers such as capacitor tissues and silk, the average quantity of mica is in the order of 65 per cent, the remainder being binder and carrier.

In the past decade, numerous inorganic materials have been tried for binders in order to increase the operating limits of electrical apparatus. The apparent limitations of all the inorganic binders are the high heat treatments or temperatures required to make the binders chemically and electrically stable. Following such heat treatments, inorganic binders lose their flexibility and become, in most cases, a brittle, crystalline structure. Therefore inorganic-bonded mica is limited to simple rigid forms such as plates and cylinders. The large number of plasticizers and synthetic resins now available has improved the retention of flexibility in organic binders and varnishes. A specific example of the improvement in the heat resistance of varnish films within the last six years is represented by the following data which we have collected on varnished cambric cloth.

The test procedure in determining the respective heat resisting properties of the varnish film is accomplished by hanging narrow tapes (approximately one inch in width by six inches to ten inches in length) in ovens maintained at temperatures of 100 degrees centigrade and 125 degrees centigrade plus or minus 2, degrees, respectively. Samples are withdrawn at regular intervals and bent around a one-eighth-inch diameter mandrel. A checking or cracking of

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the varnish film is considered as the end point or failure and the total number of hours is recorded for the particular sample. In 1932 the average life of varnished cloth was in the order of 500 to 600 hours at 100 degrees centigrade, and 100 to 150 hours at 125 degrees centigrade. Today the special varnished cloths of comparable thicknesses are capable of withstanding in the order of 2,500 to 3,000 hours at 100 degrees centigrade, and 350 to 450 hours at 125 degrees centigrade. By sacrificing some of the electrical properties, the heat resistance can still be greatly improved on certain grades of varnished cambric cloth. It is recognized that in view of the fact that the entire surface of the varnish film is exposed to the oxidizing and/or polymerizing action of the atmosphere, the rate is considerably greater than would be encountered in practical applications of multiple layers. Therefore a correlation between test data and practical experience must be made for each condition encountered.

Because of basic differences between varnish-coated products of class *A* insulation and the combinations of mica and coils for class *B* insulation, it is difficult to establish reliable test methods for determining heat-resisting properties. The binders for the mica products must first have a certain minimum degree of adhesion to hold the splittings in place in addition to the other electrical and physical requirements; second, due to the overlapping laminated structure of the mica films, tests such as tensile strength, tearing, bending, etc., are unreliable because they depend essentially upon the carrier and not the over-all combination of the insulation.

It appears that the only dependable and satisfactory way in which to determine the aging characteristics and temperature limits of class *B* insulation is to apply them to the individual unit of electrical apparatus where such variations as heating and cooling cycles, expansion and contraction, vibration, high and low humidities, corrosive vapors and gases, etc., are present.

Doctor T. S. Taylor's paper on "Repeated Thermal Expansions and Contractions and Their Effect Upon Long Armature Coil Insulations" (AIEE, 1924) is the only specific data that can be found on this subject. A model of four slots having an over-all length of 110 inches was built up from punchings. Ventilating ducts $^1/_2$ inch and $1^1/_4$ inches wide were included in an attempt to duplicate present engineering practice. Eight coils, two per slot, were insulated with various types of class *B* mica-tape insulation. The model was subjected to heating and cooling cycles with increasing temperatures of 75, 100, 130, and 160 degrees centigrade for a total of some 11,500 periods. Following each series of tests a potential of 37,000 volts was applied from conductor to ground with no breakdowns. At the duration of the experiment, an examination of the coils disclosed that the carriers and binders were completely destroyed in and near the several air ducts and that considerable deterioration had occurred in the slot section. I refer to this paper somewhat in detail for predicating the following comments.

First, for the relatively short period of time consumed in making these observations as compared to several years of operating life of the normal motor, temperatures in the order of 160 degrees centigrade were sufficient to destroy the organic carriers of the mica films and the bonding properties of the varnishes.

Second, in and near the air ducts, where the insulation was not mechanically supported, and also subjected to a higher rate of oxidation, there was excessive deterioration and swelling of the composite structure.

Third, the dielectric properties of the mica were not affected as evidenced by the high potential tests.

Fourth, in the absence of vibration and continuous voltage stresses, the individual factors of expansion and contraction of these long coils did not have a deleterious effect upon the insulation.

If the model had been subjected to vibration and electrical stresses comparable to conditions found in practice, it is quite possible that some of the mica films would have shifted, particularly those in and near the air duct; also there would no doubt have been added deterioration due to ionization in the spaces created by the volatilization and disintegration of the binder and carrier.

Thermal conductivity of a given insulation and indirectly its life, is a function of its density or compactness. Therefore, if the best composite insulation now being made should be loosely applied and poorly impregnated, its ability to withstand elevated operating temperatures would be seriously reduced. This factor alone probably accounts for the large deviations in the operating life of electrical apparatus. Any time-temperature relationships should also take into consideration the compactness of the coil as well as its intimate physical contact with the slot walls or other supporting and heat-conducting mediums.

If it were possible to analyze failures on the basis of those due to vibration versus pure dielectric breakdown, we would no doubt become more critical and active in establishing standards for the former. The swelling or protruding of the coil insulation due to the normal coefficient of expansion of the composite structure and possible volatilization of the bond at elevated temperatures in the air ducts and at the end of the slots creates a localized mechanical problem. Continued vibration may be sufficient to pulverize both the carrier and mica at these areas. At the higher operating voltage stresses the swelling of the coils may also introduce ionization in the coil structure.

Where space factor or the minimum frame size for a given horsepower output is limited such as, railway motors, the AIEE have established separate and special operating temperature limits for the class *B* insulation. The permissible hot spot temperature has been increased from 125 degrees centigrade to 175 degrees centigrade. Quite frequently the heat generated by the $I^2R$ losses in starting and the core losses due to higher operating flux densities exceed 175 degrees centigrade on motors having insufficient thermal capacity. Unless some emergency exists, the duration of these excessive temperatures is for relatively short periods of time and therefore gives a reasonable operating life for the motor. The deteriorating effects of the higher operating temperatures and the extreme conditions of vibration and weather on the insulation of railway motors is in most cases of secondary importance to the maintenance of time schedules. To obtain a reasonable operating life at these temperatures the insulation must be essentially inorganic such as mica and asbestos or glass fibers. Special attention must be given or changes in design made to see that the mica splittings in the entire coil structure are mechanically held in place and prevented from slipping. The common flat iron or heating element employing organic-bonded micanite heater plate is a typical and comparable example showing that if the mica is mechanically held in place the operating temperatures can be materially increased above the present AIEE temperature limits.

The mica splittings used in class *B* insulation have two outstanding physical advantages over other flexible inorganic materials such as asbestos and glass fibers. First, due to the solid and nonporous structure, the surface leakage path is tremendously increased. Second, moisture or water is adsorbed by the laminations of the mica splittings and does

# A Discussion of Proposed ASA Transformer Standards

By R. T. HENRY
FELLOW AIEE

THE proposed American Standards Association standards for transformers, regulators, and reactors which are about to be circulated for a trial period involve several departures from previous standards.

The temperature rise has been separated from the ambient and total temperatures. It is the temperature rise which determines the amount of material required and therefore the rating; whereas the ambient and total temperatures are involved only in the operation and life of the insulation and have little or nothing to do with the rating.

Insulation levels have been established in zones for dielectric tests instead of basing the tests on rated voltage. These insulation levels are based on the level of protection available in the various voltage classes.

The proposed standards include impulse tests in addition to the low-frequency dielectric tests. These impulse tests are specified in kilovolts instead of gap spacings.

The insulation strength of transformers, regulators (except induction type), constant-current transformers, and instrument transformers have been co-ordinated, thus providing the same insulation strength for various types of apparatus of corresponding voltage ratings. The insulation levels for both power and distribution transformers have been made the same for 23 kv and above.

The test code has been enlarged and brought up to date and now includes complete instructions for making the various tests on transformers, etc.

The proposed guides for operation of transformers recognize the fact that the life of insulation depends not only on the temperature but on the duration of such temperature as well and that while transformers can be operated with a copper temperature of 95 degrees centigrade (55 degrees centigrade rise at 40 degrees centigrade ambient) for limited periods without serious damage, continuous operation at such temperatures would reduce the life of the insulation to a few years at best. The recommendations for loading are therefore based on a *maximum* ambient temperature of 40 degrees centigrade but a *daily average* ambient temperature of 30 degrees centigrade.

The guides also recognize that the permissible continuous loading is greater than the rating at low ambient temperatures and less than the rating at high ambient temperatures. In addition, the guides recognize that transformers can carry appreciable overloads for limited periods and the recommendations provide for short-time overloads for recurrent conditions and higher short-time overloads for emergency conditions.

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A paper presented under the auspices of the AIEE committee on electrical machinery at the AIEE winter convention, New York, N. Y., January 23–27, 1939.

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not materially reduce the dielectric strength because of the nonabsorption characteristics of the individual laminations. The interstices of the asbestos and glass fibers must be filled with a varnish or compound to give additional dielectric strength above that of the air. Until suitable inorganic varnishes are developed, the most logical type of class *B* insulation having the highest over-all electrical and temperature limitations would be one composed of mica splittings and asbestos or glass fibers.

Notwithstanding the apparent improvements in varnishes, binders, and new carriers or base materials, we must recognize that either the electrical or physical limitations of class *B* insulation are still dependent upon *organic* substances and until they are radically changed or supplanted by inorganic binders and varnishes having suitable electrical and physical properties, plus stability at higher temperatures, we must not overlook this factor in proposing changes in general standards for operating-temperature limits of electrical apparatus.

In view of the variables which are so difficult to measure and correlate, any standards of temperature limits must, of necessity, be a compromise between the conservative viewpoint of low operating temperatures, reliability, long life, high efficiency, and the liberal viewpoint of lower first costs by reduction of size, higher operating temperatures, shorter life, reduced efficiencies, higher maintenance cost, and possible shut-downs for major repairs. Several years of operating experience has proved the AIEE standards for class *B* insulation, that is, a maximum hot-spot temperature of 125 degrees centigrade to be a fair and practical compromise.

The available information in regard to time-temperature characteristics of electrical insulation of all types as applied to electrical apparatus, is very meager. It would therefore seem very desirable for both the manufacturers and the operating companies to undertake a definite program for the investigation of this important subject. Any information thus found would be to the mutual knowledge and advancement of our engineering society.

# Asbestos and Glass-Fiber Magnet-Wire Insulation

By K. N. MATHES
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MAGNET WIRE may be divided into class *O*, class *A*, class *B*, and class *C*, on the basis of the AIEE temperature ratings.[1] Many types of class *O* or class *A* magnet-wire insulations are in common use. The variety of class *B* magnet wire insulations is, for obvious reasons, much more limited. Different types are listed in table I.

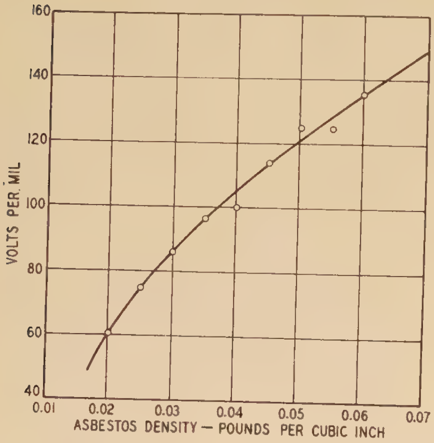

**Figure 1. Volts per mil versus density of dry asbestos**

Thickness 25 mils

Felted asbestos fiber has been prominent as a class *B* fibrous magnet-wire insulation. The recently developed commercial production of glass-fiber-insulated magnet wire has created considerable interest. This paper is limited to a consideration of the properties and application of these two types of class *B* fibrous constructions.

Class *B* magnet wire is used principally where high temperatures are encountered. The temperature stability of insulation, however, cannot be considered alone as it is qualified by many other factors when considering a particular application. In some cases flexibility may be of first importance and an extremely heat-resistant impregnating material, which may become brittle and crack, cannot be used. Heat resistance may have to be sacrificed in order to obtain the necessary degree of flexibility. Similarly insulation may be subjected to higher temperatures when not exposed to conditions of moisture. It is important, therefore, to study many other properties of a class *B* magnet wire even though the temperature stability may be of primary importance.

## Conclusion

The temperature limitations of class *B* magnet wire must be studied in terms of many related factors. The stability of the associated varnish is one of the most important considerations. Where good moisture resistance must be retained, operating temperatures should be restricted to approximately 125 degrees centigrade in order to preserve the varnish film.

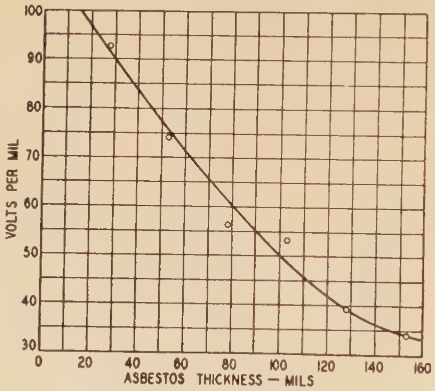

**Figure 2. Volts per mil versus thickness of dry asbestos**

Density 0.035 pound per cubic inch

Experience has indicated that for many types of service conditions and with the proper material reasonable insulation life can be expected for a range of temperatures from about 125 to 175 degrees centigrade. Of course insulation life decreases rapidly at the higher temperatures. In special applications, which are completely free from vibration and where dielectric requirements are not severe, operation at temperatures above 175 degrees centigrade may be permitted. The designer of electrical apparatus must correlate these factors to suit his particular problem.

The advantages of asbestos-insulated magnet wire in class *B* operating service are well established.

Glass-fiber magnet-wire insulation is finding an important field of use in electrical apparatus. The superior electrical properties and possibility of decreased space factor are important in many applications, and further improvements can be expected as development proceeds. Glass-fiber insulation is still too new to permit the presentation of extensive information concerning its life under service conditions.

## Properties of Unvarnished Asbestos and Glass Fiber

In the analysis of any electric insulation wherein several components comprise the whole, it is essential to give careful consideration to the selection of these components and evaluate their individual characteristics.

The term "asbestos" is a commercial term applied to any mineral which can be readily separated into more or less flexible fibers. Asbestos is a heat-resisting nonmetallic mineral silicate including two groups—the serpentine or chrysotile group (hydrous silicates of magnesium) and the amphibole group (metasilicates of magnesium, calcium, iron, sodium, and aluminum, with a little water of hydration).

**Table I**

| | | |
|---|---|---|
| Continuous (enamel) | Inorganic oxide bound with organic binder[2] | Inorganic material coated with organic material[3] |
| Ribbon | Asbestos paper | Paper or cloth baked mica tape |
| Fibrous | Varnished asbestos fiber | Varnished glass fiber |

**Table II**

| Property | Asbestos | Glass Fiber |
|---|---|---|
| Fusing point (degrees centigrade) | 1,550[4] | About 700 |
| Yield point (loss of resilience) (degrees centigrade) | No significance | 550 to 600 |
| Dehydration temperature* (degrees centigrade) | Over 385 | None |
| Stress - relieving temperature (degrees centigrade) | No significance | Above approximately 150 |
| Acid resistance | Fair | Good (attacked by hydrofluoric) |
| Resistance to corona | Decomposes slowly producing magnesium nitrate | Unaffected |

*Loss of water of hydration (chemically combined water).

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[1] For all numbered references, see list at end of paper.

Chrysotile asbestos is the variety commonly used in the electrical industry. Due to the fineness of fibers, and their strength and flexibility, it can be carded for felting or spun into roving (a soft rope-like material) for application to wire in much the same manner as other textile materials.

The flexibility of asbestos is closely related to the combined water content, which, in the chrysotile variety, averages 14 per cent and accounts for its superiority to all other types. Flexibility is maintained consistently at all temperatures below 385 degrees centigrade.[4] At higher temperatures the water of hydration is gradually driven off and the fibers can be easily pulverized. From a consideration of heat resistance alone, it can be said therefore, that asbestos possesses ample margin for all magnet-wire applications in motor and generator armature and field coils.

Emphasis must be placed on two factors; magnetic iron and surface impurities (conducting salts present on the surface of all asbestos fibers). Magnetic iron cannot be separated from the fiber commercially and extreme care must be used in the selection of a source having a low content (0.50 per cent maximum of magnetic iron for nonferrous grades) which is so generally dispersed that the possibility of large particles, causing grounds between turns in apparatus coils, is remote. The same care must be exercised in selection to obtain material free from surface conducting salts since it has definitely been proved that the dielectric strength is not so much dependent upon the basic asbestos as on the amount of surface impurities present which have a great affinity for moisture.

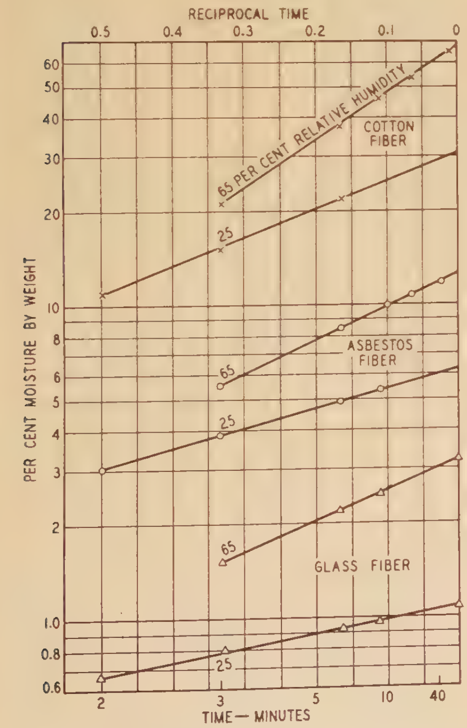

**Figure 3. Increase in per cent moisture versus minutes at 25 per cent and 65 per cent relative humidity, at 25 degrees centigrade**

Samples conditioned 16 hours at 150 degrees centigrade

The dielectric properties of untreated dry asbestos fiber plotted as a function of density and thickness are illustrated in figures 1 and 2.

Asbestos fiber for electrical insulation is graded as number 1 or number 2 depending upon the average length as determined by screen test. The asbestos fiber is mixed with cotton to facilitate textile operations, 10–15 per cent being the usual average content for magnet-wire materials. The fiber is processed into laps for direct application or spun into roving (either with or without a cotton core) and wound on suitable packages for spiral wrapping on the conductor.

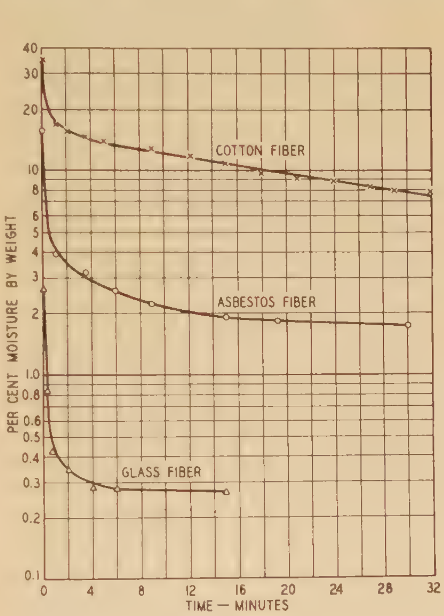

**Figure 4. Decrease in per cent moisture versus minutes at 50 per cent relative humidity and 25 degrees centigrade**

Samples conditioned at 100 per cent relative humidity and 40 degrees centigrade

Glass fiber is a synthetic material of definite composition and quality. The commercial production of glass fiber has been described previously.[5] Textile fiber glass may be classified as staple fiber (6 to 8 inches long) and continuous filament. The fibers are 0.00025 inch in diameter or smaller. Because of the enormous surface area of the fine glass fibers, severe weathering and low electrical surface resistivity may be experienced unless the fibers are drawn from excellent electrical glass. An alkali-free glass has been developed for electrical purposes which has high surface electrical resistivity and good resistance to ordinary moisture conditions. The alkali-free glass may disintegrate under some steam conditions and is not as stable as asbestos in this respect.

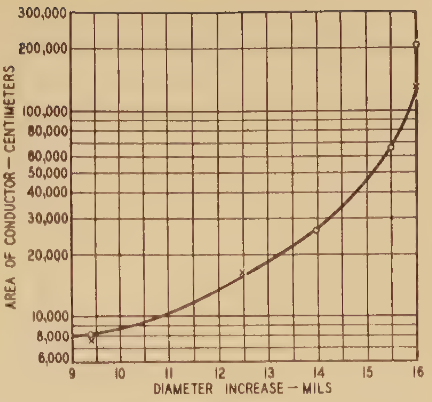

**Figure 5. Maximum insulation increase for round double-cotton- or double-glass-insulated magnet wire**

⊙—National Electrical Manufacturers' Association values for cotton

The surface of the glass fiber is particularly sensitive to cutting or nicking by adjacent fibers and must be protected by a sizing material possessing proper lubricating and binding properties. The sizing material used at present contains hygroscopic materials which impair the electrical and physical properties. In addition, the sizing is somewhat corrosive to copper and is not truly compatible with most insulating varnishes.

Although the glass fiber does not permit volume absorption of moisture, it cannot strictly be called nonhygroscopic since electrical properties may be damaged by moisture picked up in the following ways:

1. Adsorption on the glass-fiber surface.
2. Absorption in sizing material.
3. Capillary action between fibers or threads.
4. Capillary action between fiber and surrounding varnish.

The per cent regain and loss of weight for unvarnished cotton, asbestos, and glass fiber as a function of time at various humidities are given in figures 3 and 4. The potential advantages of glass fiber can be emphasized by comparison with the asbestos fiber which is truly a bundle of extremely fine fibers with surfaces contaminated by conducting salts.

For use as wire insulation, both staple and continuous glass fiber are used. Staple-fiber yarn is tightly spun, bonds together well because of its relatively rough finish, and can withstand greater

Table III

| Property | Cotton | Asbestos | Glass |
|---|---|---|---|
| Space factor | See figure 5 | Same as double cotton | Same as cotton (One half that of cotton with special glass) |
| Uniformity | Good | Fair | Good |
| Abrasion resistance | Superior | Adequate for coil applications | Inferior to asbestos for sharp-edged surfaces but may be superior to asbestos for smooth rubbing surfaces (adequate for coil applications when proper consideration is given to the tension device) |
| Impact resistance (see figure 6) | Fair to good | Fair | Very good |
| Flexibility | Good. Double wrap superior to single wrap | Fair, for round wire. Poor, for large rectangular sizes | Good. Double wrap superior to single wrap. Slightly inferior to cotton |
| Stiffness due to insulation (Important in small wire sizes) | Less than single glass | Less than single glass | Single but not double wrap exhibits considerable stiffness |
| Bonding (depends somewhat on varnish treatment) | Good | Good | Fair to good. Staple-fiber insulation bonds better than continuous filament |

elongation than continuous-filament yarn. In contrast, continuous-filament yarn can be softly spun, yet is stronger, more resistant to abrasion, and smoother in appearance than staple-fiber yarn. Continuous-filament yarn is available in much finer sizes than staple-fiber yarn, which is used where heavy insulation thicknesses are desired and varnish saturation is difficult to secure.

A number of other basic properties listed in table II are of interest in the comparison of asbestos and glass fiber.

## Properties of the Insulated Wire

In brief, two principal factors are of interest in connection with magnet wire:

1. The ease of handling and the ability to withstand the factory winding operation and electrical tests.

2. The design characteristics (temperature rise, space factor, etc.) which will allow a reasonable insulation life under service conditions.

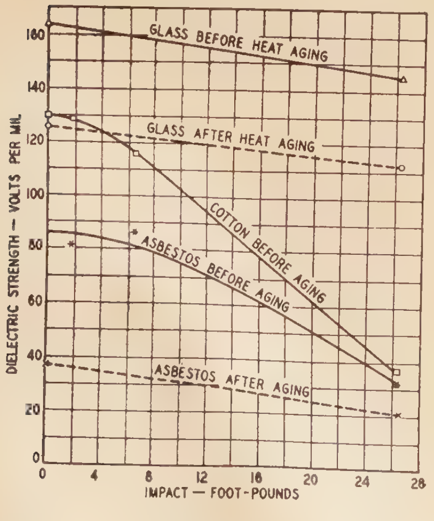

Figure 6. Dielectric strength versus increasing impact

Up to the present time generally accepted test methods are not available to evaluate completely the relative merits of fibrous magnet-wire insulations. As a result, practical experience must be combined with improved test methods to indicate the relative value of the insulation.

In many cases magnet wire may receive its most severe test in the factory during winding and assembly. Not only flexibility and resistance to abrasion but elongation and impact strength may be of extreme importance.

Laboratory tests cannot hope to duplicate all types and combinations of service conditions, but can be made under controlled conditions. Tests on magnet wire may be divided into three classifications:

1. Tests on the wire itself.

2. Tests on built-up coils to represent conditions present in various types of apparatus.

3. Tests on apparatus.

Each method of test has certain advantages and serves as a guide post in the over-all analysis. Most laboratory tests are accelerated—one or more conditions are made extreme in order to shorten the time of test. Accelerated test results must be carefully interpreted and only relative results can be expected. Long time tests (extended over a period of months with a variety of conditions, such as temperature, moisture, and voltage cycles) have much more significance in terms of actual operating service. Even long time test results serve only to indicate relative values of different types of insulation and cannot be extrapolated to indicate the absolute life under operating conditions, particularly since a combination of conditions not present in the test may be the deciding factor.

Once in place, insulation must meet a combination of various types of service conditions. The most practical criteria of a particular wire insulation comes from an analysis of actual operating results. The problem, however, sometimes is complicated by the difficulty of determining, after a failure in the field, which portion of the system failed first and the reason.

Various physical properties of cotton-covered and varnish-treated asbestos- and glass-fiber-insulated wire are compared in table III.

### FLEXIBILITY

When bent or stretched, a felted insulation such as asbestos exhibits an uneven thinning of the insulation in certain spots. In contrast, a wrapped fiber insulation such as glass fiber spreads more evenly—the parallel threads, when properly applied, tend to separate slightly and maintain a constant space factor. The superior flexibility of a wrapped-thread type of insulation becomes of practical importance when large wires must be bent on short radii without damage or when small wires may be subject to elongation from automatic winding machines.

Table IV

| | Abrasion Resistance (Average Turns per Mil of Insulation Thickness to Cause Failure) | | | |
|---|---|---|---|---|
| | Asbestos | | Glass Fiber | |
| | Large Wire | Small Wire | Large Wire | Small Wire |
| As received | 35 | 44 | 19.2 | 89 |
| Exposed one month to 170 to 180 degrees centigrade | 0.48 | 25 | 1.1 | 5.9 |

### IMPACT RESISTANCE

Ability to withstand impact is important when wire must be forced into place. A comparison of the dielectric strength of asbestos-, glass-fiber-, and cotton-insulated wire wound into coils and subjected to increasing direct impacts is given in figure 6.

### HEAT STABILITY

The quantitative appraisal of class *B* wire insulation is particularly difficult. The permissible operating temperature depends on many factors and the length of life expected. It is necessary to discuss the relative effect of exposure to high temperatures on the physical and dielectric properties.

Deterioration of physical properties may be even more important than impaired electrical properties. It is precisely this factor which is also most difficult to measure. The effect of vibration and conditions caused by temperature cycles encountered in service cannot easily be duplicated in the laboratory. Abrasion and impact tests are made which may serve as an indication of resistance to such conditions in service. Table IV indicates the effect of temperature on the relative resistance of asbestos- and glass-fiber-insulated wire to the abrasion of smooth, tungsten-carbide rods in the form of a rotating cylindrical cage.

By referring to figure 6 again the effect of heat aging can be observed by comparing the position of the dotted to the solid curves. Glass is superior to asbestos in this respect.

Table V indicates the relative effect of exposure at 170 to 180 degrees centigrade on the dielectric strength of asbestos- and glass-fiber-insulated magnet wire. It is important to recognize that these tests were made on wire placed in a well-ventilated oven, and that aging occurs much more rapidly than when the wire is sealed deep in apparatus where oxygen is largely excluded. A month of exposure of 170 to 180 degrees centigrade was sufficient to damage the varnish film and thereafter the rate of deterioration was slower.

Both asbestos and glass must be considered as physical spacing mediums. Failures or loss of dielectric strength under high heat and moisture conditions are primarily failures of the treating materials used in the insulation system.

### MOISTURE RESISTANCE

Insulation resistance is one accepted criterion of the effect of moisture on insulation in coils. The average insulation resistance between parallel wires of wound coils is plotted as a function of time at 100 per cent relative humidity and 40 degrees centigrade in figure 7. These coils were wound to duplicate field coils and were completely varnish treated. The upper curve indicates the possibility of improvement in the moisture resistance of glass insulation. In this case the original sizing was removed from the glass fiber and replaced with an improved material before varnish treatment.

## Application of Class B Magnet Wire

No sweeping conclusions should be drawn from this compilation of data. Although tests show glass-insulated wire as definitely superior to asbestos in electrical properties, the mechanical properties after exposure to high temperature may be inferior in some respects. Since glass-fiber insulation is so new, only preliminary service data have been collected; years of experience have proved the serviceability of asbestos insulation.

Keeping in mind the effect of temperature on various properties, it is possible to divide approximately the types of application for both asbestos- and glass-fiber-insulated magnet wire into three divisions based on operating temperatures as listed below.

1. Temperatures up to 125 degrees centigrade—For reasonable life the film of the binding varnish is not seriously impaired and relatively good moisture and physical and dielectric properties are retained.

2. Temperatures from 125 to 175 degrees centigrade—Film structure of varnish deteriorates but sufficient varnish may remain to act as a binder. Moisture resistance, electrical and physical properties are somewhat impaired.

3. Temperatures above 175 degrees centigrade—The binding varnish is destroyed. Electrical and particularly physical properties are considerably impaired.

In most cases operating temperatures above 175 degrees centigrade are impossible because vibration and wear destroy the insulation mechanically.

It is perhaps too early to compare extensively the field of application for asbestos- and glass-fiber-insulated magnet wire. For the larger size of wires, the increased cost of glass-fiber insulation must be justified, either by increased quality or by saving in over-all cost.

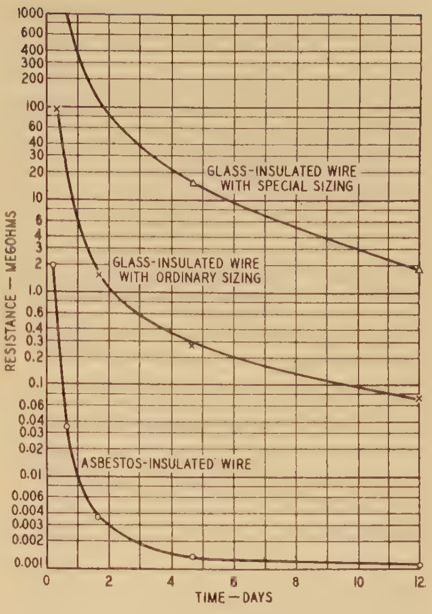

**Figure 7. Electrical resistance versus days at 100 per cent relative humidity and 40 degrees centigrade**

Table V

| | Dielectric Strength (Volts Per Mil) | | |
|---|---|---|---|
| | Asbestos Average* | Single Glass Average* | Double Glass Average** |
| Wire as received, tested at 25 degrees centigrade, 50 per cent relative humidity | 87.5 | 191 | 170 |
| Wire as received, and exposed 16 hours at 40 degrees centigrade, 100 per cent relative humidity | 29.8 | 105 | 85 |
| Wire exposed one month at 170 to 180 degrees centigrade, tested at 25 degrees centigrade, 50 per cent relative humidity | 53.4 | 146 | 114 |
| Wire exposed one month at 170 to 180 degrees centigrade, exposed 16 hours at 40 degrees centigrade, 100 per cent relative humidity | 11.3 | 41 | 32 |

*Average of 20 results on different sizes of wire from 0.0201 to 0.114 inch.
**Average of five results on 0.72-inch wire.

The following two factors should be studied:

1. Possibility of decreased space factor, resulting in smaller motors or increased copper area with the same slot space and resulting greater output or efficiency.

2. Possibilities for saving in labor.

## Method of Manufacture

A commonly used method of asbestos magnet-wire manufacture consists of wrapping asbestos roving spirally around the conductor, applying compound, and removing the excess with suitable polishing dies. With this method, uniformity of the insulation is limited by the uniformity of the roving which, in the smaller sizes, is difficult to control. Low production speeds result because of lack of strength when the finer sizes of roving are used, and this method is generally limited to large wires with insulation increases greater than for double cotton.

A method whereby the asbestos is felted on the wire was introduced in recent years which permits the application of carded asbestos directly to the wire, giving a homogeneous, intertangled mass of asbestos at all points on the conductor. Improved space factor, greater density of insulations, more uniformity, and reduced cost are achieved. Wire sizes from number 30 to 4/0 can be readily insulated maintaining double cotton insulation increases or less in special applications. With greater density and uniformity improved dielectric strength has resulted. This method has one deficiency—loss of insulation flexibility on larger sizes of rectangular wire which may be overcome by the use of proper treating materials.

Since glass fiber is so readily twisted into strong, fine thread, it is applied in this form to wire. The yarn is wound with parallel ends in a universal winding and is applied by wrapping the ribbon of parallel ends around the wire as it runs through the wrapping machine in a manner very nearly the same as that used with cotton or silk. Care is used to eliminate sharp edges and unnecessary rubbing surfaces in order to reduce abrasion and friction to a minimum. Since the yarn has very little extensibility, the insulating process must be very precise to avoid yarn breakage.

Staple glass fiber has been applied to wire directly as it comes from the fiber-making machine in the form of a wrapped sliver of parallel filaments. Wire insulated in this way does not have the density nor uniformity of a wrapped-thread type of insulation.

Fibrous-insulated class *B* magnet wire must be compound or varnish treated in order to attain sufficient abrasion resistance to be suitable for winding operations. An adequate treatment should give the wire the following characteristics:

1. Good abrasion resistance—obtained by adequate bonding, penetration, and filling of the interstices between fibers.
2. Hard and smooth surface film.
3. Good flexibility.

These desirable qualities are functions of the following factors:

1. Type and nature of treating varnish or compound.
2. Method used to secure penetration.
3. Temperature and degree of baking.

Because so many factors are concerned, no one exact method can be described at this time for varnish or compound treatment of fiber-insulated wire.

## References

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# Lightning Performance of 110- to 165-Kv Transmission Lines

A GREAT MANY papers have been presented in recent years on the subject of lightning as it affects the electrical industry and particularly transmission lines. Quite a few of these papers have dealt with the lightning performance of high-voltage lines in service covering individual systems in various sections of the country.

A committee paper was presented in 1935 on "Lightning Performance of 220-Kv Lines"[1] which summarized and discussed the records of some 19 lines in the 220-kv class comprising practically all lines of that voltage operating in the United States and Canada. This type of record with its broad inclusive coverage of lightning performance of lines was received with so much favor that it was recommended by the AIEE power transmission and distribution committee that the lightning and insulator subcommittee collect and present similar records giving the lightning performance of high-voltage lines in the general voltage classification of 132 kv. The data and discussion presented in this paper have resulted from the above situation.

## Scope and Plan

In collecting data on these higher-voltage lines, it was decided to include the transmission voltage range from 110 kv up to 165 kv, inclusive, for lines operating in the United States and Canada.

The data were obtained by sending a questionnaire to companies who either operated or had under their control lines in the above classification. The questionnaire included 71 questions which were designed to give principally what was considered important information on line construction and line operation and to bring out outstanding features which might throw some light on the lightning performance of these lines over the past ten years. Some information not directly connected with the lightning performance of the line was requested and has been included in the data presented herewith.

Each company was asked its opinion as to whether the ten-year lightning performance of each of its lines was satisfactory, and if not, what types of improvement were being considered. The detailed questionnaire with accompanying prints of typical towers and counterpoise designs is too lengthy to reproduce here, but the pertinent data received has been tabulated, analyzed, and discussed.

## Extent of Lines Reported

The questionnaire was sent out to 35 companies in the United States and Canada. Operating records and data were received from 24 companies. Four companies reported that they had no lines in the voltage range indicated and seven companies failed to send in an answer. It will therefore be seen that of the 35 companies contacted, the response to the committee attempt to get information in this way has been most gratifying, replies having been received from 70 per cent of the companies.

It is interesting to note that of the 24 companies sending in data, records have been received on lines operating in 20 states in the United States and also from Canada. The lightning severity as shown by the isokeraunic level where these lines operate ranges from 22 storms to 68 storms per year, that is a ratio of slightly over three to one.

Table I gives in some detail the character of the transmission lines on which data were obtained. The table shows that the records cover 7,140 miles of line (right of way) of which 3,890 are of two-circuit, steel-tower construction; 1,725 of single-circuit steel construction; and 1,526 of single-circuit, wood construction. Fifty-four per cent of the mileage is of 132-kv construction; 31 per cent of 110-kv rating; and the balance distributed among the other voltage classes.

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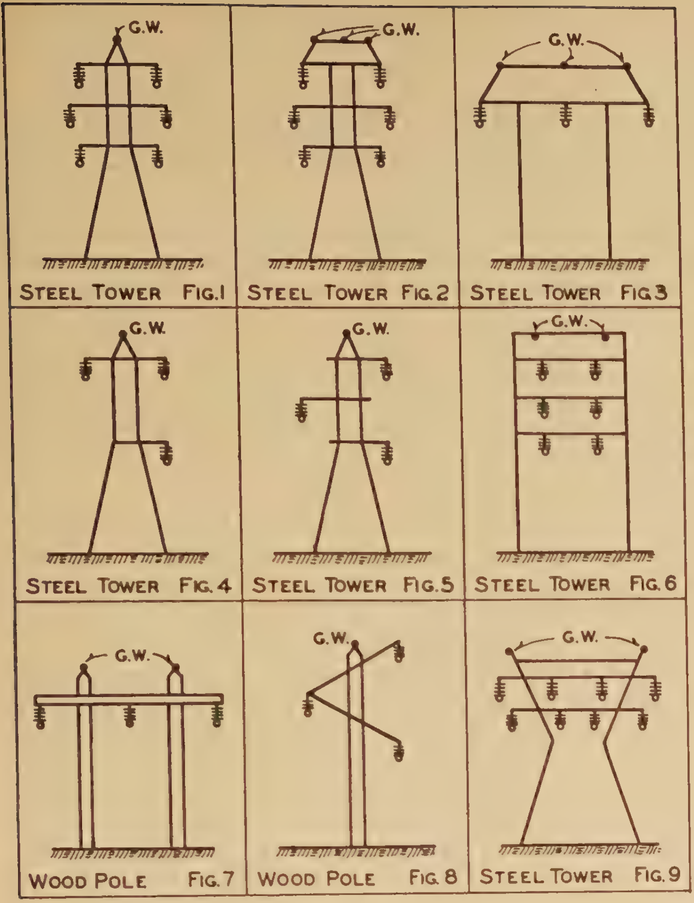
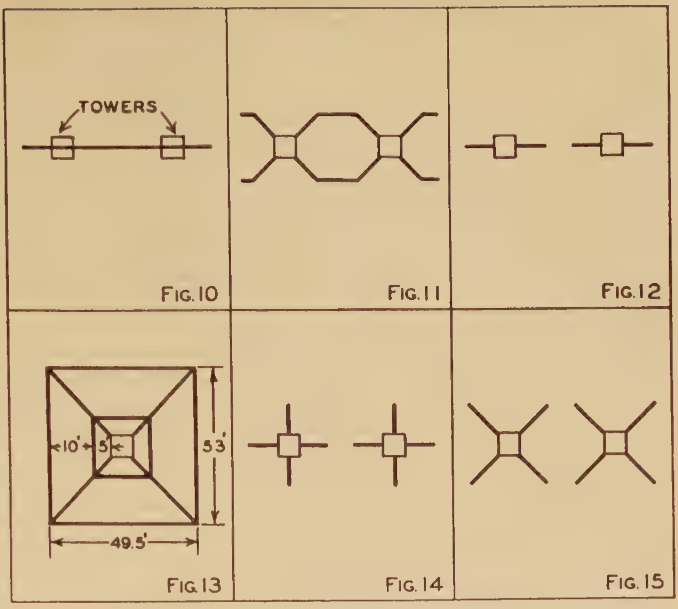
Personnel of AIEE lightning and insulator subcommittee: Philip Sporn, *chairman;* H. A. Frey, I. W. Gross, D. C. Jackson, Jr., W. W. Lewis, J. T. Lusignan, F. W. Packer, and C. F. Wagner.

The committee wishes to acknowledge the wholehearted co-operation of the contributing companies who have generously contributed data to make this report possible and their prompt response in answering the questionnaire on which the data presented in this report were based. It also acknowledges the assistance of G. D. Lippert of the American Gas and Electric Service Corporation in preparing the data received into suitable form for analysis as given herein.

[1] AIEE Lightning Reference Book, page 1272.



**Figures 1–9. Typical transmission structures**



**Figures 10–15. Typical counterpoises**

All the lines operate at 60 cycles unless otherwise noted in footnotes 1 and 2 of the table.

## Presentation and Discussion of Data

It has not been possible to include all the data received as a result of the questionnaire, but the major part of it, particularly that which covers the lightning characteristics of the line and its lightning performance, has been correlated and tabulated in table II. The names of the companies and lines are given by symbol only as a result of a specific request by a few companies that company name and line be withheld from publication.

While replies to the questionnaire were in most cases complete and carefully prepared, in a few cases some questions were apparently misunderstood with the result that the data submitted presented some difficulties in interpretation. However, such instances are few and it is believed that any errors of interpretation placed on the data sent in are of minor importance.

**Table I. Miles of Three-Phase Line (Right of Way)**

Wood-Pole and Steel-Tower Construction

| Line Kilovolts | Single Circuit Wood | Single Circuit Steel | Double Circuit Wood | Double Circuit Steel | Total |
|---|---|---|---|---|---|
| 165 | | | | 135.2 | 135.2 |
| 154 | 89.5 | | | 28.7 | 118.2 |
| 140 | | 283.3 | | 52.7 | 336.0 |
| 132 | 593.3 | 1,076.7 | | 2,181.6* | 3,851.6 |
| 120 | 37.6 | | | 274.1 | 311.7 |
| 115 | | 37.3 | | 110.6 | 147.9 |
| 110 | 806.0 | 326.9 | | 1,107.4† | 2,240.3 |
| Totals | 1,526.4 | 1,724.2 | | 3,890.3 | 7,140.9 |

Total wood........1,526.4
Total steel........5,614.5

Total...........7,140.9

* Includes 31.5 miles of four-circuit single-phase 25-cycle line.

† Includes 171.9 miles of 25-cycle line.

### TOWER AND COUNTERPOISE CONFIGURATION

In figures 1 to 9 are given the typical tower structures in use as tabulated in column 7. Likewise, figures 10 to 15 give types of counterpoise configuration, where used, as listed in column 21 of table II.

### GROUND WIRES

The effect of ground wires in reducing lightning outages is shown both in table III and figure 16. From table III it appears where no ground wire is used, single-circuit steel lines show an average of 29.8 outages per hundred miles of line per year; with one ground wire, the outages figure becomes 9.8; and with two ground wires 7.0. The same general type of reduction is shown for wood-pole construction although the figure of 0.44 outages for the single-circuit, wood line with one ground wire is probably questionable for comparison purposes as it includes the record of only one line.

The benefit in going from one ground wire to two is clearly indicated in table III where the outages on two-circuit steel lines drop from 7.1/4.2 to 5.2/3.5 as the ground wires are increased from one to two. The figures separated by the slant indicate outages per hundred miles of line per year, the first figure before the (/) being for single-circuit outages and the second figure for two-circuit outages. These figures for two-circuit steel tower lines give a ratio of 1.36 for single-circuit and 1.20 for double-circuit outages as between the one-ground-wire and the two-ground-wire arrangement. For single-circuit steel-tower lines the ratio

TABLE II

# LIGHTNING PERFORMANCE AND

| COMPANY | LINE | LINE CONSTRUCTION | | | | | | | | | | | | | | | | | LIGHTNING PROTECTION | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | K.V. | CIRCUITS | MILES (R.W.) | STEEL - WOOD | STRUCT. (FIG. N°) | CONDUCTOR HEIGHT AT TOWER MIN.-(FT.) | | | GR. W. HEIGHT (FT.) ABOVE TOP COND. | INSULATORS | | | CLEARANCE-LINE TO STRUCTURE (IN.) COND. SWING (DEG.) | CONDUCTOR ALUM.-COP. | ARMOR RODS | VIBRATION DAMPERS | AVG. SPAN (FT.) | GROUND WIRES | COUNTERPOISES | | GROUND RODS | | GR. RES. OF STRUCTURES | | |
| | | | | | | | TOP | MID. | BOT. | | SPACING (INCHES) | NUMBER | | | | | | | | FIG. N° | % OF LINE | PER TOW. | % OF LINE | AVG. | | MAX |
| | | | | | | | | | | | | SUSP. | D.E. | | | | | | | | | | | BEFORE CP.-GR. | AFTER CP.-GR. | AFTER CP.-GR. |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 |
| 1 | A | 132 | 1 | 82.5 | S | 3 | 52 | 52 | 52 | 11.8 | 5¾ | 10 | 12 | 62/50 | A | YES | YES | 1000 | 2 | 13 | 68 | — | 1 | 7.9 | — | 18 |
| 2 | A | 110 | 1 | 38.8[11] | W | 7 | 30 | 30 | 30 | 5.1 | 5½ | 6 | 7 | 36/45 | A | NO | YES | 632 | 0 | NO | 0 | 1 | 100 | 91 | 81.7 | 260 |
| 2 | AA | 110 | 1 | | S | — | 30 | 30 | 30 | 8 | 5½ | 7 | 8 | 42/45 | A | YES | NO | 645 | 1 | NO | 0 | 0 | 0 | — | — | — |
| 2 | B | 120 | 1 | 37.6 | W | 7 | 30 | 30 | 30 | 5.7 | 5 | 8 | 9 | 42/45 | A | YES | NO | 491 | 0 | NO | 0 | — | — | — | — | — |
| 2 | C | 110 | 1 | 55.3 | W | 7 | 60 | 50 | 40 | 5.7 | 5⅛ | 7 | 8 | 38/45 | A | YES | NO | 460 | 0 | NO | 0 | — | — | — | — | — |
| 2 | D | 110 | 2 | 52.9 | S | 2 | 60 | 60 | 60 | 9 | 5⅛ | 8 | 9 | — | C | NO | NO | 881 | 2 | NO | 0 | 0 | 0 | — | — | — |
| 3 | A | 154 | 2 | 28.7 | S | 1-3 | 36 | 36 | 36 | 12.6 | 5 | 10 | 12 | 55/- | A | YES[3] | NO | 977 | 1 | NO | 0 | NO | 0 | — | — | — |
| 4 | A | 115 | 2[4] | 16.5 | S | 3 | 46 | 46 | 46 | 8 | 5¾ | 9[5] | 9 | 36/45 | C | NO | YES | 600 | 2[6] | NO | 0 | NO | 0 | — | — | — |
| 4 | B | 115 | 2[4] | 30.6 | S | 3 | 46 | 46 | 46 | 8 | 5¾ | 9[5] | 9[5] | 36/45 | C | NO | YES | 600 | 2[6] | NO | 0 | NO | 0 | — | — | — |
| 4 | C | 115 | 2[4] | 13.2 | S | 3 | 46 | 46 | 46 | 8 | 5¾ | 9[5] | 9[5] | 36/45 | C | NO | YES | 600 | 2[6] | NO | 0 | NO | 0 | — | — | — |
| 4 | D | 115 | 2[4] | 20.7 | S | 3 | 46 | 46 | 46 | 8 | 5¾ | 9[5] | 9[5] | 36/45 | C | YES | YES | 600 | 2[6] | NO | 0 | NO | 0 | — | — | — |
| 4 | E | 115 | 1 | 19.5 | S | 3 | 46 | 46 | 46 | 8 | 5¾ | 9[5] | 9[5] | 36/45 | C | NO | YES | 600 | 2 | NO | 0 | NO | 0 | — | — | — |
| 4 | F | 115 | 1 | 17.8 | S | 3 | 46 | 46 | 46 | 8 | 5¾ | 9[5] | 9[5] | 36/45 | C | NO | YES | 600 | 2 | NO | 0 | NO | 0 | 460 | — | — |
| 8 | A | 132 | 2 | 11.9 | S | 2 | 100 | 87 | 74 | 13 | 5½ | 9 | 11 | 42/45 | A | NO | NO | 790 | 2 | NO | 0 | NO | 0 | 2.9 | — | — |
| 8 | B | 132 | 2 | 10.9 | S | 2 | 100 | 87 | 74 | 13 | 5¾ | 9 | 11 | 42/45 | A | NO | NO | 814 | 2 | NO | 0 | NO | 0 | 9.4 | — | — |
| 8 | C | 132 | 2[4] | 4.5 | S | 2 | 100 | 87 | 74 | 13 | 5¾ | 9 | 11 | 42/45 | A | NO | NO | 795 | 2 | NO | 0 | NO | 0 | 10.6 | — | — |
| 8 | D | 132 | 2 | 23.4 | S | 2 | 100 | 87 | 74 | 13 | 5½ | 9 | 11 | 42/45 | A | NO | NO | 840 | 2 | NO | 0 | NO | 0 | 12.4 | — | — |
| 8 | E | 132 | 2 | 28.8 | S | 2 | 97 | 84 | 71 | 13 | 5½ | 9 | 11 | 42/45 | A | NO | YES | 512 | 2 | NO | 0 | NO | 0 | 25.8 | — | — |
| 9 | A | 110[b] | 2 | 23.6 | S | 2 | 70 | 60 | 50 | 8.5 | 5⅜ | 6 | 8 | 60/30 | C | NO | NO | 560 | 2 | NO | 0 | NO | 0 | — | — | — |
| 13 | A | 132 | 1 | 79.9 | S | 1 | 69 | 57 | 45 | 10 | 5 | 10 | 11 | 48/45 | A | YES | YES[7] | 880 | 1 | NO | 0 | NO | 0 | — | — | — |
| 13 | B | 132 | 1 | 54.0 | S | 1 | 76 | 64 | 52 | 10.7 | 5 | 10 | 11 | 48/45 | A | YES | YES[7] | 970 | 1 | NO | 0 | NO | 0 | — | — | — |
| 13 | C | 132 | 1 | 26.4 | S | 5 | 69 | 57 | 45 | 10 | 5 | 10 | 11 | 48/45 | A | YES | YES[7] | 880 | 1 | NO | 0 | NO | 0 | — | — | — |
| 13 | D | 132 | 1 | 8.2 | S | 1 | 76 | 64 | 52 | 10.3 | 5 | 10 | 11 | 48/45 | A | YES | YES[7] | 970 | 1 | NO | 0 | NO | 0 | — | — | — |
| 13 | DD | 132 | 1 | 23.9 | S | 1 | 75 | 63 | 51 | 10.3 | 5 | 10 | 11 | 51/45 | C | NO | NO | 770 | 1 | NO | 0 | 2 | 100 | — | — | — |
| 14 | A | 132 | 1 | 14.8 | S | 1 | 76 | 64 | 52 | 9.3 | 6 7/16 | 9 | 11 | 45/45 | C | NO | NO | 701 | 1 | NO | 0 | NO | 0 | — | — | — |
| 15 | A | 132 | 1[8] | 30.9 | S | 2 | 74 | 61 | 48 | 9 | 6½ | 8 | 8 | 60/30 | C | NO | NO | 500 | (a) | NO | 0 | 2 | 100 | — | 3 | 5 |
| 15 | B | 132 | 1[8] | 27.9 | S | 2 | 74 | 61 | 48 | 9 | 6½ | 8 | 8 | 60/30 | C | NO | NO | 500 | (a) | NO | 0 | 2 | 100 | — | 3 | 5 |
| 15 | C | 132 | 1 | 30.9 | S | 2 | 81 | 68 | 55 | 10.4 | 6½ | 8 | 8 | 60/30 | C | NO | NO | 500 | 1 | NO | 0 | 2 | 43 | — | 3 | 5 |
| 15 | D | 132 | 1[c] | 42.2 | S | 2 | 84 | 71 | 58 | 9 | 6½ | 8 | 8 | 60/30 | C | NO | NO | 880 | (a) | 11 | 3 | 2 | 45 | — | 10 | 50 |
| 15 | E | 132 | 1[c] | 61.7 | S | 2 | 84 | 71 | 58 | 9 | 6½ | 8 | 8 | 60/30 | C | NO | NO | 880 | (a) | 11 | 3 | 2 | 43 | — | 10 | 50 |
| 15 | F | 132 | 1 | 24.4 | S | 2 | 84 | 71 | 58 | 10.4 | 6½ | 8 | 8 | 60/30 | C | NO | NO | 880 | 1 | NO | 0 | NO | 0 | 10 | — | — |
| 15 | G | 132 | 1 | 29.7 | S | 2 | 84 | 71 | 58 | 9 | 6½ | 8 | 8 | 60/30 | C | NO | NO | 880 | 1 | NO | 0 | 2 | 85 | — | 10 | 67 |
| 15 | H | 132 | 2 | 36.9 | S | 2 | 84 | 71 | 58 | 9 | 6½ | 8 | 8 | 60/30 | C | NO | NO | 880 | 2 | NO | 0 | 2 | 51 | — | 8 | 25 |
| 15 | I | 132 | 1 | 10.6 | S | 2 | 84 | 71 | 58 | 9 | 6½ | 8 | 8 | 60/30 | C | NO | NO | 880 | 2 | NO | 0 | 2 | 56 | — | 10 | 30 |
| 16 | A | 110 | 1 | 79.4 | W | 7 | 43 | 43 | 43 | — | 5½ | 8 | 9 | 31/45 | C | NO | NO | 509 | 0 | NO | 0 | NO | 0 | — | — | — |
| 16 | B | 110 | 1 | 83.7 | W | 7 | 49 | 49 | 49 | 10.5 | 5¾ | 8 | 9 | — | A | YES | NO | 592 | 2 | NO | 0 | 2 | 100 | — | — | — |
| 17 | A | 132 | 1 | 50.3 | S | 1 | 70 | 58 | 46 | 8.5 | 4¾ | 10 | 12 | 47/50 | A | NO | NO | 588 | 1 | NO | 0 | NO | 0 | — | — | — |
| 17 | B | 132 | 1 | 27.9 | S | 1 | 70 | 58 | 46 | 8.5 | 4¾ | 10 | 12 | 37/50 | C | NO | NO | 608 | 1 | NO | 0 | NO | 0 | — | — | — |
| 17 | C | 132 | 1 | 22.4 | S | 1 | 70 | 58 | 46 | 8.5 | 4¾ | 10 | 12 | 47/50 | C | NO | NO | 612 | 1 | NO | 0 | NO | 0 | — | — | — |
| 17 | D | 132 | 1 | 29.4 | S | 1-2-6 | 70 | 58 | 46 | 8.5 | 4¾ | 10 | 12 | 47/50 | A-C | NO | NO | 588 | 1-2 | NO | 0 | 4 | ? | — | 1.96 | 4.8 |
| 17 | E | 132 | 1 | 22.8 | S | 1-2 | 72 | 59 | 47 | 9.5 | 5¾ | 9/11 | 12/14 | 37/50 | C | NO | NO | 602 | 1-2 | NO | 0 | 4 | ? | — | 3.5 | 14.1 |
| 17 | F | 132 | 1 | 7.9 | S | 1 | 72 | 59 | 47 | 9.5 | 4¾ | 10 | 12 | 37/50 | C | NO | NO | 591 | 1 | NO | 0 | NO | 0 | — | — | — |
| 17 | G | 132 | 1 | 52.3 | S | 1-2-6 | 70 | 58 | 46 | 8.5 | 4¾ | 10/12 | 12/14 | 37/50 | A-C | NO | NO | 590 | 1-2 | NO | 0 | 4 | ? | — | 2.2 | 14.1 |
| 17 | H | 132 | 1 | 76.1 | S | 1 | 70 | 58 | 46 | 8.5 | 4¾ | 10 | 12 | 37/50 | A | NO | NO | 603 | 1 | NO | 0 | NO | 0 | — | — | — |
| 18 | A | 132 | 1 | 5.8 | S | 1 | 76 | 63 | 50 | 11 | 5 | 10 | 12 | 48/38 | C | NO | NO | 644 | 1 | NO | 0 | 2-3 | (d) | — | — | — |
| 18 | B | 132 | 2 | 18.0 | S | 1 | 76 | 63 | 50 | 11 | 5 | 10 | 12 | 48/38 | C | NO | NO | 680 | 1 | NO | 0 | 2-3 | (d) | — | — | — |
| 18 | C | 132 | 2 | 18.0 | S | 1 | 76 | 63 | 50 | 11 | 5 | 10 | 12 | 48/38 | C | NO | NO | 680 | 1 | NO | 0 | 2-3 | (d) | — | — | — |
| 18 | D | 132 | 2 | 8.9 | S | 1 | 76 | 63 | 50 | 11 | 5 | 10 | 12 | 48/38 | C | NO | NO | 715 | 1 | NO | 0 | 2-3 | (d) | — | — | — |
| 18 | E | 132 | 1 | 8.9 | S | 1 | 76 | 63 | 50 | 11 | 5 | 10 | 12 | 48/38 | C | NO | NO | 715 | 1 | NO | 0 | 2-3 | (d) | — | — | — |
| 18 | F | 132 | 2 | 9.9 | S | 1 | 76 | 63 | 50 | 11 | 5 | 10 | 12 | 48/38 | C | NO | NO | 710 | 1 | NO | 0 | 2-3 | (d) | — | — | — |
| 18 | G | 132 | 2 | 9.9 | S | 1 | 76 | 63 | 50 | 11 | 5 | 10 | 12 | 48/38 | C | NO | NO | 710 | 1 | NO | 0 | 2-3 | (d) | — | — | — |
| 18 | H | 132 | 2 | 6.4 | S | 1 | 76 | 63 | 50 | 11 | 5 | 10 | 12 | 48/38 | C | NO | NO | 650 | 1 | NO | 0 | 2-3 | (d) | — | — | — |
| 18 | I | 132 | 1 | 6.1 | S | 1 | 76 | 63 | 50 | 11 | 5 | 10 | 12 | 48/38 | C | NO | NO | 675 | 1 | NO | 0 | 2-3 | (d) | — | — | — |
| 18 | J | 132 | 2 | 5.1 | S | 1 | 76 | 63 | 50 | 11 | 5 | 10 | 12 | 48/38 | C | NO | NO | 715 | 1 | NO | 0 | 2-3 | (d) | — | — | — |
| 18 | K | 132 | 2 | 6.5 | S | 1 | 76 | 63 | 50 | 11 | 5 | 10 | 12 | 48/38 | C | NO | NO | 680 | 1 | NO | 0 | 2-3 | (d) | — | — | — |

FOR FOOT NOTES SEE END OF THIS TABLE.

# CONSTRUCTION OF 110 KV. TO 165 KV. LINES

| GRADING & ARC DEVICES[1] | FAULT CLEARING TIME (CYCLES) | | | LINE OPERATION | | | | | | | | | | | | | | LIGHTNING TERRITORY[2] | ISOCERAUNIC LEVEL | OPERATING RECORD SATISFACTORY | CONSIDERING IMPROVEMENTS TO BETTER LINE PERFORMANCE | COMPANY | LINE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | RELAYS | | OCB (MIN) | YEARS IN SERVICE | OUTAGES DUE TO LIGHTNING ONE CIRCUIT / TWO CIRCUIT | | | | | | | | | | AVG. OUTAGES/100 MILE OF LINE/YEAR | CASES OF | | | | | | | |
| | PRIMARY (MIN.) | BACK UP (MIN.) | | | 1928 | 1929 | 1930 | 1931 | 1932 | 1933 | 1934 | 1935 | 1936 | 1937 | | BURNED DOWN CONDUCTORS | PROLONGED OUTAGES | | | | | | |
| 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 1 | 2 |
| RR | — | INST. | 15 | 7 | — | — | 0 | 0 | 0 | 3 | 2 | 1 | 3 | 1 | 1.5 | 1 | 4 | S | 50 | NO | YES | 1 | A |
| T | 3 | — | 8 | 4 | — | — | — | — | — | — | 17 | 5 | 8 | 12 | 28.7 | 0 | 0 | H | 40 | — | — | 2 | A |
| T | 3 | — | 8 | 4 | | | | | | | | | | | | 1 | 1 | H | 40 | — | — | 2 | AA |
| P-T[5] | 3 | — | 8 | 5 | — | — | — | — | — | 13 | 15 | 6 | 16 | 22 | 38.0 | 0 | 0 | H | 40 | — | — | 2 | B |
| P | 15 | 48 | 8 | 5 | — | — | — | — | — | 9 | 16 | 12 | 10 | 16 | 23.0 | 0 | 0 | H | 40 | — | — | 2 | C |
| RR-P[6] | 12 | 66 | 8 | 5 | — | — | — | — | — | 15 | 10 | 2 | 16 | 10 | 20.0[6] | 0 | 0 | H | 40 | — | — | 2 | D |
| HH[3] | 4 | — | 8 | 10 | 0/9 | 0/5 | 0/14 | 0/6 | 0/6 | 0/8 | 0/10 | 0/11 | 0/15 | 0/8 | 0/35.5 | 0 | 1 | S | 62 | NO | YES-T. | 3 | A |
| RR | 1 | 25 | 8 | 12 | 3/0 | 3/2 | 4/5 | 0/1 | 3/0 | 10/3 | 3/0 | 4/0 | 6/0 | 5/1 | 25/7.3 | 0 | 0 | M | 22 | YES | NO | 4 | A |
| RR | 1 | 16 | 8 | 11 | 4/0 | 8/0 | 5/0 | 1/0 | 3/0 | 5/0 | 2/0 | 4/0 | 5/0 | 6/0 | 14/0 | 0 | 0 | M | 22 | YES | NO | 4 | B |
| RR | 1 | 35 | 8 | 9 | — | — | 0/0 | 2/0 | 0/0 | 0/0 | 0/0 | 0/0 | 1/0 | 1/0 | 3.8/0 | 0 | 0 | M | 22 | YES | NO | 4 | C |
| RR | 1 | 16 | 17 | 9 | — | 0/0 | 7/1 | 0/0 | 0/0 | 6/0 | 1/0 | 1/0 | 7/0 | 4/0 | 14/0.5 | 0 | 0 | M | 22 | YES | NO | 4 | D |
| RR | 3 | 20 | 17 | 7 | — | — | — | 1 | 4 | 1 | 1 | 2 | 4 | 0 | 9.5 | 0 | 0 | M | 22 | YES | NO | 4 | E |
| RR | 1 | 5 | 8 | 1 | — | — | — | — | — | — | — | — | — | 4 | 22.5 | 0 | 0 | M | 22 | YES | NO | 4 | F |
| RH | 6 | 120 | 6 | 10 | 0/0 | 0/0 | 0/0 | 0/0 | 1/0 | 0/0 | 0/0 | 0/0 | 0/0 | 1/0 | 1.8/0 | 0 | 0 | M | 28 | YES | NO | 8 | A |
| RR | 6 | 180 | 12 | 9 | 0/0 | 2/0 | 1/0 | 0/0 | 0/0 | 0/1 | 0/0 | 0/0 | 1/1 | 0/0 | 3.6/1.8 | 0 | 0 | M | 28 | YES | NO | 8 | B |
| RR | 6 | 168 | 12 | 9 | 0/0 | 2/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/1 | 4.4/2.2 | 0 | 0 | M | 28 | YES | NO | 8 | C |
| RR | 6 | 174 | 6 | 9 | — | 0/0 | 0/0 | 0/1 | 0/0 | 0/0 | 0/0 | 0/0 | 0/1 | 0/0 | 0/1 | 0 | 0 | M | 28 | YES | NO | 8 | D |
| RR | 12 | 150 | 12 | 9 | — | 0/1 | 1/1 | 1/0 | 0/0 | 1/1 | 3/2 | 3/1 | 3/1 | 2/2 | 5.4/3.5 | 0 | 0 | M | 28 | NO | YES-CP. | 8 | E |
| NO | 18 | 120 | 18 | 26 | 0 | 0 | 1 | 2 | 0 | 4 | 3 | 2 | 4 | 1 | 7.2[6] | 0 | 0 | S | 35 | YES | YES-CP. & GR. RDS. | 9 | A |
| LH | 3 | 42 | 13 | 11 | 1 | 3 | 4 | 6 | 5 | 1 | 1 | 5 | 3 | 2 | 3.9 | 0 | 0 | H | 40 | YES | YES-REDUCE GR. RES. | 13 | A |
| LH | 3 | 15 | 13 | 9 | 0 | 3 | 0 | 1 | 2 | 2 | 5 | 3 | 2 | 3 | 3.9 | 0 | 0 | H | 40 | YES | YES-REDUCE GR. RES. | 13 | B |
| LH | 3 | 29 | 13 | 12 | 1 | 0 | 0 | 0 | 1 | 0 | 2 | 1 | 1 | 2 | 3.0 | 0 | 0 | M | 40 | YES | YES-REDUCE GR. RES. | 13 | C |
| LH | 3 | 29 | 8 | 11 | | | | | | | | | | | | 0 | 0 | M | 40 | YES | YES-REDUCE GR. RES. | 13 | D |
| LH | 3 | 29 | 8 | 11 | — | — | — | — | 3 | 0 | 1 | 1 | 9 | 6 | 7.1 | 0 | 0 | M | 40 | YES | NO | 13 | DD |
| NO | 1 | 60 | 8 | 10 | | | | | | | | | | | | 3 | 4 | M | 40 | YES | NO | 14 | A |
| LR | 5 | NO | 16 | 14 | 2 | 1 | 0 | 1 | 0 | 2 | 0 | 0 | 0 | 0 | 1.9 | 0 | 0 | S | 42 | YES | NO | 15 | A |
| NO | 5 | NO | 16 | 11 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.35 | 0 | 0 | S | 42 | YES | NO | 15 | B |
| RR[6] | 2 | NO | 16 | 7 | — | — | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0.41 | 0 | 0 | S | 42 | YES | NO | 15 | C |
| NO | 5 | NO | 16 | 11 | — | — | — | — | — | 0 | 2 | 1 | 1 | 2 | 2.75 | 0 | 0 | S | 42 | YES | NO | 15 | D |
| NO | 5 | NO | 11 | 9 | — | 0 | 1 | 6 | 0 | 1 | 0 | 1 | 2 | 0 | 2.0 | 0 | 0 | S | 42 | YES | NO | 15 | E |
| RR[6] | 5 | NO | 11 | 8 | — | 0 | 2 | 1 | 2 | 0 | 1 | 1 | 0 | 1 | 7.3 | 0 | 0 | S | 42 | YES | NO | 15 | F |
| NO | 1 | NO | 16 | 13 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1.0 | 0 | 0 | H | 42 | YES | NO | 15 | G |
| NO | 1 | NO | 16 | 10 | 0/0 | 0/0 | 0/1 | 1/0 | 0/0 | 1/0 | 1/0 | 1/0 | 1/0 | 1/0 | 1.5/0.3 | 0 | 0 | H | 42 | YES | NO | 15 | H |
| NO | 1 | NO | 16 | 13 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0.9 | 0 | 0 | H | 42 | YES | NO | 15 | I |
| HH | 12 | NO | 9 | 9 | — | — | — | — | 6 | 23 | 33 | 15 | 13 | 23 | 24 | 0 | 2 | — | 33 | — | NO | 16 | A |
| — | 7 | 42 | 12 | 7 | — | — | — | — | — | — | — | 8 | 4 | 2 | 5.5 | 0 | 0 | — | 33 | — | NO | 16 | B |
| LH | 60 | NO | 12 | 14 | 6 | 7 | 7 | ? | 7 | 3 | 3 | 2 | 3 | ? | 9.5 | 0 | 0 | H | 35 | NO | NO | 17 | A |
| LH | 60 | NO | 12 | 12 | 1 | 2 | 2 | 0 | 0 | 0 | 2 | 1 | 3 | 0 | 4.0 | 0 | 0 | H | 35 | NO | NO | 17 | B |
| FC | 60 | NO | 12 | 13 | 2 | 6 | 2 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 5.8 | 0 | 0 | H | 35 | NO | NO | 17 | C |
| LH-P | 81 | NO | 12 | 7 | — | — | — | 0 | 0 | 0 | 2 | 1 | 0 | 1 | 2.0 | 0 | 0 | H | 35 | YES | NO | 17 | D |
| P-T | 31 | NO | 8 | 2 | — | — | — | — | — | — | — | — | 1 | 0 | 2.2 | 0 | 0 | H | 35 | YES | NO | 17 | E |
| FC | 27 | NO | 12 | 12 | 1 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3.8 | 0 | 0 | H | 35 | YES | NO | 17 | F |
| LH-P | 60 | NO | 12 | 2 | — | — | — | — | — | — | — | — | 1 | 0 | 1.0 | 0 | 0 | H | 35 | YES | NO | 17 | G |
| LH | 60 | NO | 12 | 12 | — | — | — | — | — | — | — | — | 3 | 5 | 5.3 | 0 | 0 | H | 35 | NO | NO | 17 | H |
| NO | — | — | — | 12 | 1 | 3 | 0 | 0 | 2 | 1 | 1 | 0 | 0 | 0 | 13.8 | 0 | 0 | M | 38 | YES | NO | 18 | A |
| NO | — | — | — | 12 | 0/0 | 3/0 | 0/0 | 2/0 | 0/1 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 2.8/0.6 | 0 | 0 | M | 38 | YES | NO | 18 | B |
| NO | — | — | — | 10 | 0 | 1/0 | 1/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 1/0 | 0/0 | 1.7/0 | 1 | 1 | M | 38 | YES | NO | 18 | C |
| NO | — | — | — | 11 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/1 | 0/0 | 0/0 | 1/0 | 0/0 | 1.1/1.1 | 0 | 0 | M | 38 | YES | NO | 18 | D |
| NO | — | — | — | 10 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 4.4 | 0 | 0 | M | 38 | YES | NO | 18 | E |
| NO | — | — | — | 1 | — | — | — | — | — | — | — | — | — | 0/0 | 0/0 | 0 | 0 | M | 38 | YES | NO | 18 | F |
| NO | — | — | — | 12 | 1/1 | 1/0 | 0/0 | 0/0 | 0/1 | 0/0 | 0/0 | 0/0 | 0/2 | 1/0 | 3.0/4.0 | 1 | 1 | M | 38 | YES | NO | 18 | G |
| NO | — | — | — | 12 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 1/0 | 2/0 | 1/0 | 6.3/0. | 0 | 0 | M | 38 | YES | NO | 18 | H |
| NO | — | — | — | 14 | 1 | 1 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 8.2 | 0 | 0 | M | 38 | YES | NO | 18 | I |
| NO | — | — | — | 5 | — | — | — | — | — | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0 | 0 | M | 38 | YES | NO | 18 | J |
| NO | — | — | — | 5 | — | — | — | — | — | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0 | 0 | M | 38 | YES | NO | 18 | K |

# TABLE II (CONTINUED) LIGHTNING PERFORMANCE AND

| LINE CONSTRUCTION | | | | | | | | | | | | | | | | | | | LIGHTNING PROTECTION | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | CONDUCTOR HEIGHT AT TOWER MIN.-(FT.) | | | | INSULATORS | | | | | | | | | COUNTER-POISES | | GROUND RODS | | GR. RES. OF STRUCTURES | | |
| | | | | | | | | | | | | NUMBER | | | | | | | | | | | | AVG. | | MAX |
| COMPANY | LINE | K.V. | CIRCUITS | MILES (R.W.) | STEEL-WOOD | STRUCT. (FIG. Nº) | TOP | MID. | BOT. | GR.W. HEIGHT (FT.) ABOVE TOP COND. | SPACING (INCHES) | SUSP. | D.E. | CLEARANCE-LINE TO STRUCTURE (IN.) COND. SWING (DEG.) | CONDUCTOR ALUM.-COP. | ARMOR RODS | VIBRATION DAMPERS | AVG. SPAN (FT.) | GROUND WIRES | FIG. Nº | % OF LINE | PER TOW. | % OF LINE | BEFORE CP.-GR. | AFTER CP.-GR. | AFTER CP.-GR. |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 |
| 18 | L | 132 | 2 | 53.2 | S | 1 | 76 | 63 | 50 | 11 | 5 | 10 | 12 | 48/38 | C | NO | NO | 695 | 1 | NO | 0 | 2-3 | (d) | — | — | — |
| 18 | M | 132 | 2 | 8.1 | S | 1 | 76 | 63 | 50 | 11 | 5 | 10 | 12 | 48/38 | C | NO | NO | 700 | 1 | NO | 0 | 2-3 | (d) | — | — | — |
| 18 | N | 132 | 2 | 67.8 | S | 1 | 76 | 63 | 50 | 11 | 5 | 10 | 12 | 48/38 | C | NO | NO | 695 | 1 | NO | 0 | 2-3 | (d) | — | — | — |
| 20 | A | 140 | 1 | 148.0 | S | 1-5 | 52 | 46 | 40 | — | $4\frac{3}{4}$ | 10 | 12 | 48/20 | C | NO | NO | 520 | 0 | NO | 0 | 0 | 0 | — | — | — |
| 20 | B | 140 | 2 | 43.5 | S | 1 | 69 | 57 | 45 | 7.7 | $4\frac{3}{4}^{v}$ | 9 | 11-12 | 48/20 | C | NO | NO | 665 | 1 | NO | 0 | 0 | 0 | — | — | — |
| 20 | C | 140 | 1 | 44.3 | S | 1-5 | 52 | 46 | 40 | 6.7 | $4\frac{3}{4}$ | 10 | 12 | 48/20 | C | NO | NO | 564 | 1 | NO | 0 | $1.6^{e}$ | 100 | 39 | 19.5 | 155 |
| 20 | D | 140 | 1/2 | $38.2^{f}$ | S | 1-6 | 48 | 48 | 48 | 6.7 | $4\frac{3}{4}^{v}$ | 10 | 11-12 | 48/20 | A-C | NO | YES-NO | 710 | 2-1 | NO | 0 | $1.01^{e}$ | 100 | 65-25 | 20-8.7 | 130-55 |
| 20 | E | 140 | 1 | 62.0 | S | 1 | 64 | 52 | 40 | 7 | $4\frac{3}{4}$ | 10 | 12 | 48/20 | C | NO | NO | 517 | 1 | NO | 0 | 0 | 0 | — | — | — |
| 21 | A | 110 | 2 | 50.4 | S | 2 | 60 | 51 | 43 | 7 | 5 | 8 | 10 | — | C | NO | NO | 630 | 1 | NO | 0 | 0 | 0 | — | — | — |
| 21 | B | 132 | 2 | 189.0 | S | 1 | 85 | 74 | 63 | 12.4 | 5 | 8 | 10 | — | A | YES | NO | 1056 | 1 | 10-14 | 14 | 0 | 0 | 250 | 100 | — |
| 21 | C | 110 | 2 | 68.3 | S | 1 | 73 | 62 | 51 | 9 | 5 | 8 | 10 | — | A-C | NO | NO | 830 | 1 | NO | 0 | 0 | 0 | — | — | — |
| 21 | D | 110 | 1 | 68.3 | W | 8 | 36 | 32 | 28 | 4 | 5 | 7 | 9 | — | A | NO | NO | 330 | 1 | NO | 0 | — | 0 | — | — | — |
| 21 | E | 110 | 1 | 54.8 | S | 3 | 61 | 61 | 61 | 7 | 5 | 8 | 10 | — | A | YES | NO | 880 | 1 | 14 | 38 | 0 | 0 | 35 | 10 | — |
| 21 | F | 110 | 2 | 103.6 | S | 1 | 85 | 74 | 63 | 12.3 | 5 | 8 | 10 | — | A | YES | NO | 1056 | 1 | NO | 0 | 0 | 0 | — | — | — |
| 22 | A | 110 | 2 | 86.5 | S | 2 | 62 | 54 | 46 | 8.8 | $5\frac{7}{8}$ | 7 | 8 | 35/45 | A | NO | NO | 530 | 2 | NO | 0 | 0 | 0 | 51 | — | — |
| 22 | B | 110 | 2 | 86.5 | S | 2 | 62 | 52 | 42 | 8.2 | $4\frac{3}{4}$ | 7 | 8 | 33/45 | A | NO | NO | 530 | $1^{g}$ | NO | 0 | 0 | 0 | 51 | — | — |
| 22 | C | 165 | 2 | 135.2 | S | 2 | 74 | 62 | 50 | 9.5 | $4\frac{3}{4}$ | 10 | 12 | 44/45 | A | YES | NO | 880 | 2 | NO | 0 | 0 | 0 | 175 | — | — |
| 23 | A | $132^{i}$ | 1 | 28.4 | S | 5 | 55 | 41 | 41 | 11.9 | $5\frac{1}{8}$ | 10 | 12 | 50/45 | A | NO | YES | 1410 | 1 | NO | 0 | 0 | 0 | — | — | — |
| 23 | C | $132^{j}$ | 2 | 56.9 | S | 1 | 83 | 70 | 57 | 11.9 | $4\frac{3}{4}$ | 10 | 12 | 47/45 | A | YES | NO | 975 | 2 | 12 | 31 | 5 | 62 | — | $45.8^{k}$ | — |
| 23 | D | 132 | 1 | 30.7 | S | 1 | 85 | 70 | 57 | 10.9 | $5\frac{1}{8}$ | 10 | 12 | 50/45 | A | NO | YES | 1195 | 1 | NO | 0 | 0 | 0 | 60 | — | — |
| 23 | G | 132 | 2 | 65.0 | S | 1 | 83 | 70 | 57 | 10.9 | $4\frac{3}{4}^{v}$ | 10 | 12 | 47/45 | A | NO | YES | 1270 | 1 | 10-12-14 | 15 | 0 | 0 | 38.9 | — | — |
| 23 | H | 132 | 2 | 28.7 | S | 1 | 93 | 78 | 65 | 12.9 | $5\frac{1}{8}$ | $11^{h}$ | 12 | 50/45 | A | NO | YES | 1175 | 1 | NO | 0 | 0 | 0 | 31.5 | — | — |
| 23 | J | 132 | 2 | 89.5 | S | 1 | 83 | 70 | 57 | 10.9 | $4\frac{3}{4}^{v}$ | $12^{h}$ | 12 | 50/45 | A | YES | NO | 1000 | 1 | NO | 0 | 0 | 0 | 2.2 | — | — |
| 23 | K | 132 | 2 | 63.2 | S | 1 | 83 | 70 | 57 | 10.9 | $5\frac{1}{8}^{v}$ | 10 | 12 | 50/45 | A | YES | NO | 1100 | 1 | NO | 0 | 0 | 0 | 2.5 | — | — |
| 23 | L | 132 | 2 | 18.1 | S | 1 | 76 | 63 | 50 | 12.9 | $5\frac{1}{8}$ | 10 | 12 | 55/45 | A | NO | YES | 1620 | 1 | NO | 0 | 0 | 0 | 35.8 | — | — |
| 23 | M | 132 | 2 | 28.9 | S | 1 | 83 | 70 | 57 | 11.9 | $5\frac{1}{8}$ | 10 | 12 | 50/45 | A | NO | YES | 840 | 1 | NO | 0 | 0 | 0 | — | — | — |
| 23 | N | 132 | 2 | 80.6 | S | 1 | 83 | 70 | 57 | 11.9 | $5\frac{1}{8}$ | 10 | 12 | 50/45 | A | NO | YES | 930 | 1 | NO | 0 | 0 | 0 | — | — | — |
| 23 | O | 132 | 1 | 41.2 | S | 1 | 93 | 78 | 65 | 12.9 | $5\frac{3}{4}$ | 9 | 11 | 50/45 | A | YES | YES | 1160 | 1 | NO | 0 | 0 | 0 | — | — | — |
| 23 | P | 132 | $2^{r}$ | 73.0 | S | 1 | 83 | 70 | 57 | 10.9 | $4\frac{3}{4}$ | $11^{h}$ | 12 | 47/45 | A | YES | NO | 1320 | 1 | NO | 0 | 0 | 0 | 7.8 | — | — |
| 23 | R | 132 | 2 | 21.8 | S | 1 | 83 | 70 | 57 | 10.9 | $4\frac{3}{4}$ | 11 | 12 | 50/45 | A | YES | NO | 1160 | 1 | NO | 0 | 0 | 0 | 5.5 | — | — |
| 23 | S | 132 | 2 | 80.6 | S | 1 | 83 | 70 | 57 | 11.9 | $5\frac{1}{8}$ | 10 | 12 | 50/45 | A | YES | NO | 1065 | 1 | NO | 0 | 0 | 0 | 11.0 | — | — |
| 23 | U | 132 | 2 | 167.8 | S | 1 | 83 | 70 | 57 | 10.9 | $4\frac{3}{4}^{v}$ | 11 | 12 | 50/45 | A | YES | YES | 1240 | 1 | NO | 0 | 0 | 0 | 3.7 | — | — |
| 23 | V | 132 | 1 | 37.4 | S | 1 | 85 | 70 | 57 | 10.9 | $5\frac{1}{8}$ | 10 | 12 | 50/45 | A | NO | YES | 1200 | 1 | NO | 0 | 0 | 0 | 73.5 | — | — |
| 23 | W | 132 | 2 | 42.9 | S | 1 | 83 | 70 | 57 | 10.9 | $4\frac{3}{4}$ | $12^{h}$ | 12 | 50/45 | A | NO | YES | 1130 | 1 | NO | 0 | 0 | 0 | 79.1 | — | — |
| 23 | X | 132 | 1 | 51.8 | S | 1 | 83 | 70 | 57 | 11.9 | $5\frac{1}{8}$ | 10 | 12 | 50/45 | A | NO | YES | 1180 | 1 | NO | 0 | 0 | 0 | 21.7 | — | — |
| 23 | AA | $132^{t}$ | 2 | 35.0 | S | 1 | 83 | 70 | 57 | 11.9 | $5\frac{1}{8}$ | 10 | 12 | 50/45 | A | YES | NO | 1180 | 1 | NO | 0 | 0 | 0 | — | — | — |
| 23 | BB | 132 | 1 | 39.8 | W | 5 | 35 | 35 | 35 | — | $5\frac{3}{4}$ | 10 | 12 | — | A | NO | YES | 955 | 0 | NO | 0 | 0 | 0 | — | — | — |
| 23 | CC | 132 | 2 | 47.9 | S | 1 | 85 | 70 | 57 | 12.9 | $5\frac{1}{8}$ | 10 | 12 | 50/45 | A | NO | YES | 1260 | 1 | NO | 0 | 0 | 0 | — | — | — |
| 23 | DD | 132 | 1 | 38.9 | S | 1 | 83 | 70 | 57 | 11.9 | $5\frac{1}{8}$ | 10 | 12 | 50/45 | A | NO | YES | 1170 | 1 | NO | 0 | 0 | 0 | 42.3 | — | — |
| 23 | EE | 132 | 2 | 23.6 | S | 1-3 | 83 | 70 | 57 | 12.9 | $5\frac{1}{8}$ | 10 | 12 | 50/45 | A | NO | YES | 1240 | 1 | NO | 0 | 0 | 0 | — | — | — |
| 23 | FF | 132 | 2 | 40.5 | S | 1-3 | 83 | 70 | 57 | 13.0 | $4\frac{3}{4}^{v}$ | 10 | 12 | 47/45 | A | NO | YES | 1370 | 1 | NO | 0 | 0 | 0 | 10.9 | — | — |
| 23 | GG | 132 | 1 | 47.9 | S | 1 | 84 | 70 | 57 | 12.5 | — | — | — | — | A | NO | YES | — | 1 | NO | 0 | 0 | 0 | 6.9 | — | — |
| 23 | HH | 132 | 2 | 38.0 | S | 1 | 83 | 70 | 57 | 11.9 | $5\frac{1}{8}$ | 10 | 12 | 50/45 | A | YES | NO | 960 | 2 | NO | 0 | 5 | 52 | 24.5 | — | — |
| 23 | II | 132 | 1 | 65.4 | S | 1 | 83 | 70 | 57 | 10.9 | $5\frac{3}{4}$ | 9 | 11 | 50/45 | A | YES | YES | 1150 | 1 | NO | 0 | 0 | 0 | 2.5 | — | — |
| 23 | JJ | 132 | 2 | 4.9 | S | 1 | 83 | 70 | 57 | 10.9 | $5\frac{3}{4}$ | 9 | 11 | 50/45 | A | YES | NO | 1060 | 1 | NO | 0 | 0 | 0 | — | — | — |
| 23 | KK | 132 | 2 | 55.0 | S | 2 | 70 | 58 | 46 | 8.8 | $4\frac{3}{4}$ | 10 | 12 | 42/45 | C | — | — | 595 | 2 | NO | 0 | 0 | 0 | 12.0 | — | — |
| 23 | LL | $132^{t}$ | 2 | 18.5 | S | 1 | 83 | 70 | 57 | 11.9 | $5\frac{1}{8}$ | 10 | 12 | 50/45 | A | NO | YES | 640 | 1 | NO | 0 | 0 | 0 | 5.0 | — | — |
| 25 | A | 132 | 2 | 30.8 | S | 1 | 70 | 58 | 46 | 8.5 | $4\frac{3}{4}$ | 12 | 13 | 42/60 | A | YES | NO | 814 | 1 | NO | 0 | 0 | 0 | — | — | — |
| 25 | AA | 132 | 2 | 27.6 | S | 2 | 68 | 55 | 42 | 12.3 | $5\frac{3}{4}$ | 11 | 13 | 48/45 | C | NO | NO | 800 | 2 | NO | 0 | 0 | 0 | — | — | — |
| 25 | B | 132 | 2 | 119.6 | $S^{w}$ | 2 | 70 | 54 | 40 | 20.5 | $5\frac{3}{4}$ | 11 | 13 | 66/45 | C | NO | NO | 830 | 2 | NO | 0 | 0 | 0 | 6.9 | — | 56 |
| 25 | C | 132 | 1 | 135.5 | W | 7 | 33 | 33 | 33 | 10.0 | $5\frac{3}{4}$ | 11 | 13 | 42/45 | A | YES | NO | 524 | 2 | NO | 0 | (x) | 10 | — | — | 60 |
| 25 | E | $110^{p}$ | 2 | 143.6 | S | 1 | 70 | 60 | 50 | 8.3 | $5\frac{3}{4}$ | 9 | 8 | 36/45 | C | NO | NO | 755 | 1 | NO | 0 | 0 | 0 | — | — | — |
| 26 | A | 132 | $4^{h}$ | 31.5 | S | 9 | 88 | — | 72 | 18.9 | 5 | 12 | 14 | 49/54 | A | YES | NO | 930 | 2 | 11-15 | 93 | 0 | 0 | 58 | 11.4 | 30 |
| 27 | A | 115 | 2 | 29.6 | S | 2 | 60 | 50 | 40 | 11.0 | 5 | 8 | 10 | 46/48 | A | NO | NO | 528 | 2 | NO | 0 | 0 | 0 | — | — | — |
| 29 | A | 130 | 2 | 54.7 | S | 5 | 72 | 59 | 46 | 10.3 | $4\frac{3}{4}$ | 10 | 12 | 30/45 | C | NO | NO | 698 | 2 | NO | 0 | 0 | 0 | — | — | — |

FOR FOOT NOTES SEE END OF THIS TABLE.

# CONSTRUCTION OF 110 KV. TO 165 KV. LINES

| GRADING & ARC DEVICES$^{1}$ | FAULT CLEARING TIME (CYCLES) | | | LINE OPERATION | | | | | | | | | | | | | | LIGHTNING TERRITORY$^{2}$ | ISOCERAUNIC LEVEL | OPERATING RECORD SATISFACTORY | CONSIDERING IMPROVEMENTS TO BETTER LINE PERFORMANCE | COMPANY | LINE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | RELAYS | | OCB (MIN) | YEARS IN SERVICE | OUTAGES DUE TO LIGHTNING ONE CIRCUIT / TWO CIRCUIT | | | | | | | | | | AVG. OUTAGES/ 100 MILE OF LINE/YEAR | CASES OF | | | | | | | |
| | PRIMARY (MIN.) | BACK UP (MIN.) | | | 1928 | 1929 | 1930 | 1931 | 1932 | 1933 | 1934 | 1935 | 1936 | 1937 | | BURNED DOWN CONDUCTORS | PROLONGED OUTAGES | | | | | | |
| 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 1 | 2 |
| NO | – | – | – | 9 | 0/0 | 0/0 | 0/0 | 1/1 | 1/0 | 0/0 | 1/0 | 2/1 | 0/0 | 1/0 | 1.0/0.4 | 0 | 0 | M | 38 | YES | NO | 18 | L |
| NO | – | – | – | 7 | — | — | 0/0 | 0/0 | 0/0 | 0/0 | 2/0 | 0/0 | 0/0 | 0/0 | 3.1/0 | 0 | 0 | M | 38 | YES | NO | 18 | M |
| NO | – | – | – | 9 | 0/0 | 7/2 | 3/0 | 2/0 | 3/1 | 0/2 | 2/0 | 1/2 | 3/0 | 1/0 | 3.3/1.2 | 0 | 0 | M | 38 | NO | YES-GR. RDS. & CP. | 18 | N |
| LH | 12 | NO | – | 26 | 17 | 20 | 14 | 13 | 2 | 3 | 5 | 8 | 3 | 7 | 5.6 | 2 | 2 | M | 35 | YES | YES-GR. RDS & GR. WR. | 20 | A |
| LH-FC | 12 | NO | – | 13-8 | 3/0 | 4/0 | 1/0 | 1/3 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 1/0 | 2.3/0.7 | 0 | 0 | M | 35 | YES | NO | 20 | B |
| LH | 12 | NO | – | 18 | 16 | 14 | 17 | 23 | 6 | 10 | 13 | 7 | 6 | 4 | 26.2 | 1 | 1 | M | 35 | YES | YES-CP. | 20 | C |
| LH | 3 | NO | – | 10 | 0 | 3 | 1 | 2 | 0 | 2 | 5 | 0 | 4 | 1 | 4.7 | 0 | 0 | M | 35 | YES | YES-CP. | 20 | D |
| LH | 1 | NO | – | 20 | 1 | 2 | 5 | 4 | 4 | 21 | 8 | 3 | 14 | 24 | 15.8 | 2 | 3 | M | 35 | NO | YES-CP. & GR. RDS. | 20 | E |
| NO | 3 | 3 | 18 | 23 | 2 | 0 | 0 | 2 | 1 | 2 | 0 | 1 | 1 | 0 | 1.8 | 0 | 0 | L | 25 | YES | NO | 21 | A |
| NO | 3 | 3 | 18 | 6 | – | – | – | – | – | 13 | 28 | 13/5 | 13/11 | 8/11 | 4.6/6.9 | 0 | 0 | S | 25 | NO | YES-GR. W.-CP. & T. | 21 | B |
| NO | 3 | 3 | 20 | 8 | – | – | 5/0 | 0/1 | 0/0 | 2/4 | 3/4 | 0/0 | 2/1 | 3/5 | 2.8/2.4 | 0 | 0 | H | 25 | YES | NO | 21 | C |
| NO | 3 | 3 | 20 | 18 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0.44 | 0 | 1 | H | 25 | YES | NO | 21 | D |
| NO | 3 | 3 | 20 | 4 | – | – | – | – | – | – | – | 6 | 7 | 3 | 9.8 | 0 | 1 | L | 25 | NO | YES | 21 | E |
| NO | 3 | 3 | 18 | 9 | – | – | 1/1 | 1/0 | 2/1 | 5/1 | 2/0 | 2/1 | 1/2 | 4/0 | 2.2./0.7 | 0 | 0 | M | 25 | NO | YES | 21 | F |
| LH | 6 | 120 | 8 | 27 | 1/0 | 6/1 | 0/4 | 3/3 | 2/3 | 3/5 | 0/2 | 4/5 | 0/0 | 1/2 | 2.3/2.9 | NIL | 3 | M | 25 | NO | YES-CP. INST. 1938 | 22 | A |
| LH | 6 | 120 | 8 | 17 | 4/3 | 13/7 | 10/6 | 8/4 | 4/4 | 16/3 | 4/3 | 6/5 | 4/1 | 4/3 | 8.7/4.5 | NIL | 2 | M | 25 | NO | YES-CP. INST. 1938 | 22 | B |
| LH | 2 | 38 | 14 | 11 | 3/0 | 6/0 | 10/3 | 13/4 | 0/5 | 3/8 | 12/10 | 1/3 | 1/3 | 3/4 | 3.8/3.0 | NIL | 1 | M | 25 | NO | YES-CP. INST. 1938 | 22 | C |
| NO | 1 | 69 | 22 | 8 | — | — | 3 | 8 | 0 | 3 | 5 | 9 | 7 | 0 | 13.2 | 0 | 0 | S | 56 | YES | NO | 23 | A |
| RR | 1 | 29 | 22 | 8 | — | — | 4/4 | 4/2 | 3/5 | 2/2 | 2/5 | 3/13 | 5/4 | 0/5 | 4.5/8.0 | 0 | 0 | M | 27 | YES | NO | 23 | C |
| RR-T$^{L}$ | 1 | 29 | 8 | 11 | 6.3 | 10.1 | 14.5 | 11.3 | 3.8 | 8.1 | 2 | 1 | 1 | 0 | 18.8 | 0 | 0 | S | 55 | YES | NO-T NOW INST. | 23 | D |
| RH-T$^{m}$ | 3.5 | 20 | 8 | 11 | 5/2 | 19/11 | 7/4 | 15/15 | 4/2 | 5/2 | 15/1 | 5/2 | 32/8 | 10/0 | 18.0/7.3 | 0 | 0 | S | 53 | YES | NO-T & CP NOW INST. | 23 | G |
| RH | 1 | 29 | 8 | 11 | 1/1 | 6/3 | 2/3 | 6/2 | 0/0 | 3/4 | 3/3 | 1/3 | 3/4 | 4/0 | 10/8 | 0 | 0 | S | 54 | YES | NO | 23 | H |
| RR | 1 | 35 | 8 | 5 | – | – | – | – | – | 4/1 | 9/0 | 3/0 | 5/1 | 6/4 | 6/1.3 | 0 | 0 | H | 43 | YES | NO | 23 | J |
| RH | 1 | 41 | 8 | 9 | – | 0 | 3 | 16 | 3 | 5/1 | 5/1 | 5/1 | 6/0 | 4/3 | 8.3/1.9 | 0 | 0 | H | 44 | YES | NO | 23 | K |
| NO | 1 | 35 | 8 | 4 | – | – | – | – | – | – | 3/6 | 1/1 | 3/1 | 4/4 | 13.8/16.5 | 0 | 0 | S | 54 | YES | NO | 23 | L |
| RR | 1 | 46 | 8 | 9 | – | 1/0 | 2/0 | 0/0 | 0/1 | 0/0 | 2/0 | 1/0 | 3/1 | 3/0 | 4.6/0.8 | 0 | 0 | H | 45 | YES | NO | 23 | M |
| RR | 1 | 29 | 8 | 9 | – | 5/1 | 6/3 | 2/0 | 3/1 | 9/1 | 4/0 | 4/2 | 3/0 | 11/0 | 6.5/1.1 | 0 | 0 | H | 46 | YES | NO-FB NOW INST. | 23 | N |
| RH | 1 | 41 | 8 | 10 | 7 | 9 | 1 | 6 | 5 | 11 | 0 | 6 | – | – | 13.6 | 0 | 0 | H | 41 | NO | YES-GR.-CP. INST. 1938 | 23 | O |
| RH-T$^{r}$ | 1 | 41 | 8 | 13 | 10/2 | 9/2 | 1/3 | 3/5 | 3/2 | 2/4 | 16/9 | 14/9 | 6/0 | 12/1 | 10.4/5.0 | 0 | 0 | S | 45 | YES | NO | 23 | P |
| RR-RH | 1 | 18 | 8 | 13 | 2 | 1 | 0/0 | 0/1 | 0/2 | 1/1 | 0/4 | 2/0 | 5/3 | 2/0 | 6.0/6.3 | 0 | 0 | S | 46 | YES | NO | 23 | R |
| RR | 1 | 24 | 8 | 8 | – | 3 | 3 | 5 | 3 | 9 | 5/3 | 7/2 | 8/2 | 11/6 | 7.8/3.3 | 0 | 0 | H | 45 | NO | YES-GR.-CP.-T-FB. | 23 | S |
| RR | 1 | 29 | 8 | 12 | 5/7 | 24/3 | 11/1 | 19/4 | 8/5 | 10/4 | 13/3 | 10/6 | 11/4 | 11/7 | 7.7/2.6 | 0 | 0 | S | 50 | YES | NO | 23 | U |
| RR-T$^{L}$ | 1 | 41 | 8 | 11 | 7.6 | 12.1 | 17.5 | 13.7 | 4.5 | 9.7 | 1 | 3 | 7 | 12 | 23.4 | 0 | 0 | S | 55 | NO | YES-T REVAMP. | 23 | V |
| RH | 1 | 29 | 8 | 12 | 6/4 | 11/5 | 8/3 | 15/11 | 4/6 | 3/2 | 7/9 | 6/2 | 23/20 | 10/15 | 21.7/18.0 | 0 | 0 | S | 54 | NO | YES-GR.-CP.-FB. | 23 | W |
| RH | 1 | 41 | 8 | 10 | 5 | 13 | 7 | 9 | 7 | 6 | 13 | 2 | 19 | 4 | 16.4 | 0 | 0 | S | 56 | YES | NO | 23 | X |
| RR | 1 | 24 | 22 | 7 | – | – | – | 4/5 | 2/2 | 4/3 | 2/1 | 1/1 | 8/0 | 2/4 | 9.4/6.6 | 0 | 0 | S | 51 | YES | NO | 23 | AA |
| NO | 1 | 18 | 8 | 8 | – | – | 11 | 17 | 7 | 7 | 19 | 17 | 21 | 20 | 37.2 | 0 | 0 | S | 54 | NO | YES-GR.-CP. | 23 | BB |
| RH | 1 | 41 | 8 | 10 | 16/2 | 11/9 | 7/1 | 10/7 | 8/8 | 6/7 | 3/9 | 6/6 | 13/7 | 9/7 | 18.6/13.2 | 0 | 0 | S | 54 | NO | NO | 23 | CC |
| RH | 1 | 24 | 8 | 10 | 5 | 16 | 9 | 21 | 16 | 9 | 6 | 16 | 22 | 5 | 32.2 | 0 | 0 | S | 55 | NO | YES-GR.-CP-FB. | 23 | DD |
| RR | 1 | 41 | 8 | 9 | – | 4/3 | 1/2 | 3/1 | 1/1 | 1/3 | 3/1 | 5/4 | 11/8 | 0/1 | 13.6/11.2 | 0 | 0 | S | 53 | YES | NO | 23 | EE |
| RH | 1 | 41 | 8 | 12 | 12/1 | 11/4 | 4/1 | 5/5 | 2/0 | 11/3 | 8/5 | 0/2 | 11/2 | 1/3 | 16.0/6.4 | 0 | 0 | S | 54 | YES | NO | 23 | FF |
| T | 1 | 29 | 8 | 2 | – | – | – | – | – | – | – | 2 | 1 | 0 | 2.1 | 0 | 0 | S | 52 | YES | NO | 23 | GG |
| RR | 1 | 35 | 8 | 8 | – | – | 3/0 | 0/4 | 2/2 | 5/4 | 6/5 | 6/1 | 3/3 | 4/2 | 9.5/6.9 | 0 | 0 | H | 40 | YES | NO | 23 | HH |
| RH | 1 | 24 | 8 | 9 | – | 7 | 3 | 10 | 7 | 6 | 8 | 3 | 4 | 7 | 9.3 | 0 | 0 | H | 42 | NO | YES-2 CIRC. 1938 | 23 | II |
| RH | 10 | 35 | 8 | 13 | 0/0 | 1/2 | 1/0 | 0/0 | 2/1 | 0/0 | 0/0 | 2/0 | 0/1 | 1/0 | 14.3/8.2 | 0 | 0 | H | 41 | YES | NO | 23 | JJ |
| HH | 1 | 29 | 22 | 22 | 2/0 | 2/0 | 0/0 | 0/2 | 1/0 | 1/0 | 0/1 | 1/0 | 1/1 | 0/0 | 1.5/0.7 | 0 | 0 | M | 45 | YES | NO | 23 | KK |
| RR | 1 | 18 | 22 | 8 | – | – | 3/0 | 1/0 | 0/0 | 1/0 | 0/1 | 1/0 | 3/1 | 1/1 | 6.8/2.0 | 0 | 0 | H | 45 | YES | NO | 23 | LL |
| RR | INST. | 102 | 8 | 13 | – | }– | – | 1/1 | 3/1 | 0/1 | 7/0 | 8/2 | 1/0 | 6/0 | 6.4/1.2 | 0 | 0 | S | 55 | YES | NO | 25 | A |
| RR | INST. | 90 | 8 | 8 | – | }– | – | – | – | – | – | – | – | – | | 0 | 0 | S | 55 | YES | NO | 25 | AA |
| NO | INST. | 24 | 8 | 7 | – | – | – | 0/0 | 0/0 | 1/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0.12/0 | 0 | 0 | S | 55 | YES | NO | 25 | B |
| NO | INST. | 24 | 8 | 7 | – | – | – | 0 | 0′ | 1 | 1 | 0 | 0 | 0 | 0.21 | 0 | 0 | S | 55 | YES | NO | 25 | C |
| HH | 18 | NO | — | 26 | 6/0 | 2/0 | 0/0 | 2/1 | 6/0 | 0/0 | 5/0 | 2/0 | 2/0 | 1/0 | 1.8/0.07 | 1 | 1 | S | 55 | YES | NO | 25 | E |
| NO | 12 | 90 | 8 | 3 | – | – | – | – | – | – | – | 0 | 0 | 0 | 1 | 0 | 1 | H | 35 | YES | NO | 26 | A |
| LH | 18 | 51 | 12 | 8 | – | – | 0/0 | 1/1 | 0/1 | 2/2 | 1/0 | 1/0 | 0/0 | 1/0 | 2.1/1.7 | 0 | 0 | H | 45 | YES | NO | 27 | A |
| LH$^{3}$ | 28 | INST. | 12 | 24 | 0/1 | 0/0 | 0/1 | 0/0 | 0/0 | 1/0 | 0/0 | 0/0 | 1/0 | 1/1 | 0.6/0.6 | 1 | 1 | M | 35 | YES | NO | 29 | A |

| COMPANY | LINE | LINE CONSTRUCTION | | | | | | | | | | | | | | | | | LIGHTNING PROTECTION | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | K.V. | CIRCUITS | MILES (R.W.) | STEEL-WOOD | STRUCT. (FIG. Nº) | CONDUCTOR HEIGHT AT TOWER MIN.-(FT.) | | | GR.W. HEIGHT (FT.) ABOVE TOP COND. | INSULATORS | | | CLEARANCE-LINE TO STRUCTURE (IN.) COND. SWING (DEG.) | CONDUCTOR ALUM.-COP. | ARMOR RODS | VIBRATION DAMPERS | AVG. SPAN (FT.) | GROUND WIRES | COUNTER POISES | | GROUND RODS | | GR. RES. OF STRUCTURES | | |
| | | | | | | | TOP | MID. | BOT. | | SPACING (INCHES) | NUMBER | | | | | | | | FIG. Nº | % OF LINE | PER TOW. | % OF LINE | AVG. | | MAX |
| | | | | | | | | | | | | SUSP. | D.E. | | | | | | | | | | | BEFORE CP.-GR. | AFTER CP.-GR. | AFTER CP.-GR. |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 |
| 29 | B | 130 | 2 | 79.5 | S | 5 | 72 | 59 | 46 | 10.3 | 4 3/4 | 10 | 12 | 30/45 | C | NO | NO | 633 | 2 | NO | 0 | NO | 0 | — | — | — |
| 29 | C | 130 | 1 | 54.6 | W | 7 | 41 | 41 | 41 | 6.3 | 4 3/4 | 10 | 12 | 35/45 | C | NO | NO | 546 | 2 | NO | 0 | 1 | 100 | — | — | — |
| 29 | D | 130 | 1 | 79.8 | W | 7 | 41 | 41 | 41 | 6.3 | 4 3/4 | 10 | 12 | 35/45 | C | NO | NO | 513 | 2 | NO | 0 | 1 | 100 | — | — | — |
| 29 | E | 130 | 1 | 82.1 | W | 7 | 41 | 41 | 41 | 7.3 | 5 1/8 | 10 | 12 | 41/45 | C | NO | NO | 612 | 2 | NO | 0 | 1 | 100 | — | — | — |
| 29 | F | 130 | 1 | 9.6 | W | 7 | 41 | 41 | 41 | 6.3 | 4 3/4 | 10 | 12 | 35/45 | C | NO | NO | 475 | 2 | NO | 0 | 1 | 100 | — | — | — |
| 30 | A | 110 | 2 | 21.0 | S | 2 | 58 | 49 | 41 | 5.6 | 5 3/4 | 7 | 9 | 42/45 | C | NO | NO | 483 | 1 | NO | 0 | NO | 0 | — | — | — |
| 30 | B | 110 | 2 | 21.0 | S | 1-2 | 58 | 49 | 41 | 7 | 5 3/4 | 7 | 9 | 42/45 | C-A | NO | NO | 476 | 1-2 | NO | 0 | NO | 0 | — | — | — |
| 30 | C | 110 | 2 | 56.0 | S | 2 | 58 | 49 | 41 | 7 | 5 3/4 | 7 | 9 | 42/45 | A | NO | NO | 508 | 2 | NO | 0 | NO | 0 | — | — | — |
| 30 | D | 110 | 2 | 109.0 | S | 2 | 58 | 49 | 41 | 7 | 5 3/4 | 7 | 9 | 42/45 | A | NO | NO | 558 | 2 | NO | 0 | NO | 0 | — | — | — |
| 30 | E | 110 | 2 | 71.5 | S | 1-2 | 58 | 49 | 41 | 7 | 5 3/4 | 7 | 9 | 42/45 | A | NO | NO | 485 | 1 | NO | 0 | NO | 0 | — | — | — |
| 31 | A | 132 | 1 | 80.9 | W | 7 | 40 | 40 | 40 | 8.1 | 5 3/4 | 10 | 12 | 76/45 | C | — | NO | 588 | 2 | NO | 0 | NO | 0 | — | — | — |
| 31 | B | 132 | 1 | 111.0 | W | 7 | 42 | 42 | 42 | — | 5 3/4 | 9 | 11 | 79/45 | A | YES | NO | 587 | 0 | NO | 0 | 1 | 100 | — | — | — |
| 32 | A | 120 | 2 | 38.1 | S | 1 | 81 | 71 | 61 | 8 | 5 | 9 | 10 | 42/45 | C | NO | NO | 800 | 1 | NO | 0 | 1 | 100 | — | — | — |
| 32 | B | 120 | 2 | 55.5 | S | 1 | 84 | 72 | 60 | 8.5 | 5 | 9 | 10 | 42/45 | C | NO | NO | 720 | 1 | NO | 0 | NO | 0 | — | — | — |
| 32 | C | 120 | 2 | 18.1 | S | 1 | 84 | 72 | 60 | 8.5 | 5 | 9 | 10 | 42/45 | C | NO | NO | 700 | 1 | NO | 0 | NO | 0 | — | — | — |
| 32 | D | 120 | 2 | 13.3 | S | 1 | 81 | 71 | 61 | 8 | 5 | 9 | 10 | 42/45 | C | NO | NO | 740 | 1 | NO | 0 | NO | 0 | — | — | — |
| 32 | E | 120 | 2 | 35.5 | S | 1 | 81 | 71 | 61 | 8 | 5 | 9 | 10 | 42/45 | C | NO | NO | 730 | 1 | NO | 0 | NO | 0 | — | — | — |
| 32 | F | 120 | 2 | 25.8 | S | 1 | 81 | 71 | 61 | 8 | 5 | 9 | 10 | 42/45 | C | NO | NO | 740 | 1 | NO | 0 | NO | 0 | — | — | — |
| 32 | G | 120 | 2 | 16.1 | S | 1 | 81 | 71 | 61 | 8 | 5 | 9 | 10 | 42/45 | C | NO | NO | 740 | 1 | NO | 0 | NO | 0 | — | — | — |
| 32 | H | 120 | 2 | 3.6 | S | 1 | 81 | 71 | 61 | 8 | 5 | 9 | 10 | 42/45 | C | NO | NO | 600 | 1 | NO | 0 | NO | 0 | — | — | — |
| 32 | I | 120 | 2 | 15.2 | S | 1 | 81 | 71 | 61 | 8 | 5 | 9 | 10 | 42/45 | C | NO | NO | 630 | 1 | NO | 0 | NO | 0 | — | — | — |
| 32 | J | 120 | 2 | 14.5 | S | 1 | 81 | 71 | 61 | 8 | 5 | 9 | 10 | 42/45 | C | NO | NO | 680 | 1 | NO | 0 | NO | 0 | — | — | — |
| 32 | K | 120 | 2 | 20.7 | S | 1 | 81 | 71 | 61 | 8 | 5 | 9 | 10 | 42/45 | C | NO | NO | 530 | 1 | NO | 0 | NO | 0 | — | — | — |
| 32 | L | 120 | 2 | 17.7 | S | 1 | 77 | 66 | 55 | 8 | 5 | 9 | 10 | 42/45 | C | NO | NO | 470 | 1 | NO | 0 | NO | 0 | — | — | — |
| 34 | A | 110 | 1 | 71.6 | W | 7 | 44 | 44 | 44 | 8 | 5 3/4 | 7 | 12 | — | C | NO | NO | 692 | 2 | NO | 0 | 1 | 100 | — | — | — |
| 34 | B | 110 | 1 | 84.1 | W | 7 | 48 | 48 | 48 | 9.5 | 6 7/16 | 8 | 12 | — | A | YES[y] | NO | 902 | 2 | NO | 0 | 1 | 100 | — | — | — |
| 34 | C | 154 | 1 | 89.5 | W | 7 | 34 | 34 | 34 | 8.5 | 5 3/4 | 10 | 12 | — | C | NO | NO | 453 | 2 | NO | 0 | 1 | 100 | — | — | — |
| 34 | D | 110 | 2 | 48.6 | S | 2 | 63 | 53 | 43 | 7 | 5 3/8 | 7 | 8 | — | C | NO | NO | 645 | 2 | NO | 0 | NO | 0 | — | — | — |
| 34 | E | 110 | 1 | 129.3 | S | 3 | 56 | 56 | 56 | 12 | 5 1/2 | 10 | 11 | — | A | YES[y] | YES[y] | 970 | 2 | NO | 0 | NO | 0 | — | — | — |
| 34 | F | 110 | 1 | 97.4 | W | 7 | 49 | 49 | 49 | 8 | 5 3/4 | 7 | 12 | — | A | YES | NO | 828 | 2[z] | NO | 0 | 1 | 100 | — | — | — |
| 34 | G | 110 | 1 | 38.6 | W | 7 | 36 | 36 | 36 | 7.9 | 5 3/8 | 7 | 8 | — | A | NO | NO | 713 | 2 | NO | 0 | 1 | 100 | — | — | — |
| 34 | H | 110 | 1 | 130.0 | W | 7 | 52 | 52 | 52 | 8.3 | 5 3/4 | 8 | 9 | — | A | YES[y] | NO | 850 | 2 | NO | 0 | 1 | 100 | — | — | — |
| 34 | I | 110 | 1 | 58.8 | W | 7 | 45 | 45 | 45 | 6.5 | 6 7/16 | 8 | 11 | 47/30 | A | YES | NO | 910 | 2 | NO | 0 | 1 | 100 | — | — | — |
| 34 | K | 110 | 1 | 38.3 | S | 1 | 66 | 56 | 46 | 8 | 4 3/4 | 7 | 9 | 56/30 | C | NO | NO | 679 | 0 | NO | 0 | NO | 0 | — | — | — |
| 34 | L | 110 | 2 | 87.8 | S | 2 | 60 | 51 | 42 | 7.3 | 4 3/4 | 8 | 12 | 35/30 | C | NO | NO | 615 | 2 | NO | 0 | NO | 0 | — | — | — |
| 34 | M | 110 | 2 | 55.9 | S | 1 | 66 | 56 | 46 | 8.1 | 4 3/4 | 7 | 9 | 47/30 | C | NO | NO | 663 | 1 | NO | 0 | NO | 0 | — | — | — |
| 34 | N | 110 | 2 | 21.2 | S | 2 | 74 | 60 | 46 | 12.6 | 5 | 9 | 10 | 67/30 | A | YES | NO | 999 | 2 | NO | 0 | NO | 0 | — | — | — |
| 34 | O | 110 | 1 | 104.5 | S | 3 | 44 | 44 | 44 | 5.5 | 4 3/4 | 11 | 12 | 42/30 | C | NO | NO | 603 | 0 | NO | 0 | NO | 0 | — | — | — |
| 35 | A | 132 | 2 | 73.9 | S | 1 | 71 | 60 | 49 | 9.3 | 4 3/4 | 9 | 11 | 36/45 | C | NO | NO | 810 | 1 | NO | 0 | NO | 0 | — | — | — |
| 35 | B | 132 | 1 | 85.7 | S | 2 | 81 | 68 | 55 | 12.3 | 4 3/4 | 9 | 11 | 39/45 | A | NO | NO | 940 | 1 | NO | 0 | NO | 0 | — | — | — |

## FOOT NOTES TO TABLE II

(1) RR-RING AND RING; RH-RING AND HORN; LH-LINE HORN ONLY; HH-HORN AND HORN; P-THOMAS SPOONS; T-PROTECTOR TUBES; LR-LINE RING ONLY; FC-FLUX CONTROLS; FB-FAST RECLOSING, HIGH SPEED O.C.B.
(2) S-SEVERE; H-HEAVY; M-MEDIUM; L-LIGHT.
(3) ONE CIRCUIT ONLY.
(4) TWO SINGLE CIRCUIT LINES ON ONE RIGHT OF WAY.
(5) OUTSIDE CONDUCTORS ONLY-CENTER CONDUCTOR 8 UNITS.
(6) TWO PER CIRCUIT.
(7) DEAD ENDS ONLY.
(8) LINES 15A AND 15B ON SAME TOWERS (279 TOWERS) 15A ALONE ON 37 TOWERS.

(a) ONE GROUND WIRE PER CIRCUIT.
(b) TOP CONDUCTOR ONLY.
(c) 15D AND 15E ON SAME TOWERS FOR 198 TOWERS.
(d) 2 TO 3 GROUND RODS AT TOWERS WITH CONCRETE ANCHORS ONLY.
(e) GROUND RODS INSTALLED APRIL 1937.
(f) LINE IN TWO SECTIONS - 1 CIRCUIT 29 MILES / 2 CIRCUIT 9.2 MILES.
(g) ON COUNTERPOISE SECTION ONLY.
(h) 25 CYCLE SINGLE PHASE.
(i) BUILT FOR 132 KV.-OPERATED AT 44 KV.
(j) BUILT FOR 132 KV.-OPERATED AT 66 KV.

# CONSTRUCTION OF 110 KV. TO 165 KV. LINES

| GRADING & ARC DEVICES[1] | FAULT CLEARING TIME (CYCLES) |  |  | LINE OPERATION |  |  |  |  |  |  |  |  |  |  |  |  |  | LIGHTNING TERRITORY[2] | ISOCERAUNIC LEVEL | OPERATING RECORD SATISFACTORY | CONSIDERING IMPROVEMENTS TO BETTER LINE PERFORMANCE | COMPANY | LINE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | RELAYS |  | OCB (MIN) | YEARS IN SERVICE | OUTAGES DUE TO LIGHTNING ONE CIRCUIT / TWO CIRCUIT |  |  |  |  |  |  |  |  |  | AVG. OUTAGES/100 MILE OF LINE/YEAR | CASES OF |  |  |  |  |  |  |  |
|  | PRIMARY (MIN.) | BACK UP (MIN.) |  |  | 1928 | 1929 | 1930 | 1931 | 1932 | 1933 | 1934 | 1935 | 1936 | 1937 |  | BURNED DOWN CONDUCTORS | PROLONGED OUTAGES |  |  |  |  |  |  |
| 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 1 | 2 |
| LH[3] | 36 | INST. | 14 | 24 | 0/0 | 0/0 | 1/1 | 0/1 | 0/0 | 1/0 | 0/0 | 0/0 | 0/0 | 1/1 | 0.4/0.4 | 0 | 0 | M | 35 | YES | NO | 29 | B |
| NO | 23 | INST. | 13 | 20 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | M | 35 | YES | NO | 29 | C |
| NO | 34 | INST. | 22 | 20 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0.5 | 0 | 0 | M | 35 | YES | NO | 29 | D |
| NO | 30 | NO | 10 | 11 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0.5 | 1 | 1 | M | 35 | YES | NO | 29 | E |
| NO | 41 | NO | 14 | 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | M | 35 | YES | NO | 29 | F |
| NO | 1 | — | 8 | 16 | — | — | — | — | — | 9/0 | 0/0 | 1/0 | 2/0 | 0/0 | 11.4/0 | 0 | 0 | M | 30 | YES | NO | 30 | A |
| NO | 1 | — | 8 | 8 | — | — | — | — | — | 1/0 | 0/0 | 0/0 | 1/0 | 0/0 | 1.8/0 | 0 | 0 | M | 30 | YES | NO | 30 | B |
| NO | 1 | — | 8 | 15 | — | — | — | — | — | 0/0 | 1/1 | 0/1 | 0/0 | 0/0 | 0.4/0.7 | 0 | 0 | M | 30 | YES | NO | 30 | C |
| NO | 1 | — | 20 | 12 | — | — | — | — | — | 7/5 | 7/1 | 6/1 | 0/2 | 11/3 | 5.7/2.2 | 0 | 0 | M | 30 | NO | NO | 30 | D |
| NO | 1 | — | 20 | 7 | — | — | — | — | — | 8/0 | 2/1 | 2/3 | 1/0 | 3/1 | 4.5/1.4 | 0 | 0 | M | 30 | YES | NO | 30 | F |
| NO | 20 | INST. | 7 | 11 | — | — | — | — | — | — | — | — | — | 1 | 1.2 | 0 | 0 | L | 25 | YES | NO | 31 | A |
| NO | INST. | 45 | 3 | 17 | — | — | — | — | — | — | — | — | — | 0 | 0 | 0 | 0 | L | 25 | YES | NO | 31 | B |
| NO | 2 | 17 | 5 | 14 | 8/0 | 5/2 | 1/0 | 2/0 | 1/1 | 2/0 | 1/0 | 0/0 | 0/1 | 5/3 | 6.6/1.1 | 0 | 2 | H | 35 | YES | NO | 32 | A |
| LH | 2 | 15 | 5 | 10 | 2 | 1 | 3/0 | 3/0 | 2/0 | 7/0 | 4/0 | 1/0 | 2/0 | 3/1 | 5.6/0.2 | 1 | 1 | H | 35 | YES | NO | 32 | B |
| LH | 2 | 26 | 5 | 11 | 1/0 | 1/0 | 0/0 | 0/0 | 0/0 | 1/0 | 0/0 | 0/0 | 4/0 | 2/0 | 5.0/0 | 0 | 0 | H | 35 | YES | NO | 32 | C |
| LH | 2 | 32 | 5 | 14 | 7/0 | 3/0 | 1/0 | 1/0 | 1/0 | 0/0 | 0/0 | 0/0 | 0/0 | 2/0 | 11.3/0 | 0 | 0 | H | 35 | YES | NO | 32 | D |
| LH | 2 | 36 | 5 | 14 | 9/0 | 1/0 | 1/0 | 3/1 | 4/1 | 1/0 | 2/0 | 2/0 | 1/0 | 4/1 | 7.9/0.8 | 0 | 0 | H | 35 | YES | NO | 32 | E |
| LH | 2 | 33 | 5 | 13 | 2/0 | 2/1 | 1/0 | 1/0 | 2/1 | 1/0 | 2/0 | 0/0 | 2/0 | 0/1 | 5.0/1.2 | 1 | 1 | H | 35 | YES | NO | 32 | F |
| LH | 2 | 19 | 5 | 13 | 1/1 | 0/0 | 1/0 | 2/0 | 3/1 | 1/0 | 2/0 | 0/0 | 1/0 | 7/1 | 11.2/1.9 | 1 | 1 | H | 35 | YES | NO | 32 | G |
| LH | 2 | 22 | 5 | 14 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0/0 | 0 | 0 | H | 35 | YES | NO | 32 | H |
| LH | 2 | 24 | 5 | 14 | 2/0 | 0/0 | 0/0 | 1/0 | 0/0 | 1/0 | 0/0 | 1/0 | 4/0 | 0/0 | 5.9/0 | 1 | 2 | H | 35 | YES | NO | 32 | I |
| LH | 2 | 24 | 5 | 12 | 2/0 | 0/0 | 0/0 | 2/0 | 0/0 | 0/0 | 0/0 | 1/0 | 0/0 | 0/1 | 3.5/0.7 | 1 | 3 | H | 35 | YES | NO | 32 | J |
| LH | 2 | 27 | 5 | 12 | 2/0 | 2/0 | 1/0 | 0/0 | 0/0 | 1/0 | 0/0 | 2/0 | 4/0 | 3/1 | 7.3/0 | 2 | 2 | H | 35 | YES | NO | 32 | K |
| LH | 2 | 27 | 5 | 10 | 0/0 | 1/0 | 0/0 | 2/0 | 0/0 | 1/0 | 0/0 | 2/0 | 0/0 | 1/0 | 4.0/0 | 0 | 0 | H | 35 | YES | NO | 32 | L |
| LH | 1 | 75 | 8 | 13 | 22 | 6 | 2 | 4 | 5 | 3 | 8 | 0 | 11 | 3 | 9.0 | 0 | 2 | M | 68 | YES | NO | 34 | A |
| RR[Y] | 1 | 70 | 8 | 9 | – | 5 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 6 | 2.5 | 0 | 0 | H | 68 | YES | NO | 34 | B |
| LH | 1 | 60 | 8 | 11 | 10 | 6 | 7 | 4 | 7 | 9 | 6 | 7 | 12 | 7 | 8.4 | 3 | 10 | H | 68 | YES | NO | 34 | C |
| LH | 1 | 50 | 8 | 24 | 17/11 | 9/4 | 6/6 | 3/11 | 7/2 | 1/4 | 11/30 | 2/7 | 4/13 | 7/9 | 13.8/20 | 18 | 31 | H | 68 | NO | YES | 34 | D |
| RR | 1 | 60 | 8 | 10 | 37 | 14 | 7 | 17 | 18 | 19 | 23 | 15 | 38 | 17 | 15.9 | 0 | 5 | S | 68 | YES | NO | 34 | E |
| LH | 1 | 60 | 8 | 11 | 23 | 10 | 19 | 23 | 24 | 18 | 31 | 15 | 39 | 21 | 23.0 | 7 | 14 | S | 68 | YES | NO | 34 | F |
| LH | 1 | 50 | 8 | 15 | 11 | 7 | 9 | 8 | 5 | 7 | 15 | 7 | 14 | 7 | 23.4 | 2 | 5 | H | 68 | YES | NO | 34 | G |
| LH | 1 | 15 | 8 | 12 | 23 | 17 | 8 | 17 | 13 | 8 | 14 | 11 | 7 | 12 | 10.0 | 0 | 4 | S | 68 | YES | NO | 34 | H |
| NO | 20 | NO | 18 | 9 | — | — | 6 | 2 | 0 | 2 | 3 | 0 | 5 | 6 | 4.9 | 0 | 0 | H | 65 | YES | NO | 34 | I |
| NO | INST. | NO | 18 | 14 | 34 | 19 | 18 | 25 | 25 | 12 | 18 | 15 | 42 | 25 | 61.0 | 0 | 0 | H | 65 | NO | NO | 34 | K |
| NO | 10 | 60 | 18 | 25 | 7/6 | 6/1 | 10/2 | 4/7 | 6/3 | 4/4 | 10/6 | 3/4 | 27/8 | 4/1 | 9.2/4.4 | 7 | 1 | M | 65 | YES | NO | 34 | L |
| NO | INST. | 50 | 18 | 14 | 21/7 | 28/5 | 11/23 | 6/11 | 14/17 | 12/12 | 19/21 | 5/5 | 20/31 | 7/13 | 25.7/26.0 | 13 | 6 | S | 65 | NO | NO | 34 | M |
| (s) | 15 | 60 | 12 | 8 | – | – | – | 4/0 | 4/1 | 5/1 | 5/3 | 5/1 | 11/1 | 7/1 | 27.7/5.4 | 3 | 1 | M | 65 | YES | NO | 34 | N |
| NO | INST. | 90 | 8 | 13 | 56 | 24 | 27 | 37 | 29 | 13 | 46 | 16 | 50 | 41 | 22.8 | 0 | 4 | S | 65 | NO | NO | 34 | O |
| LH | 3 | NO | 5 | 13 | – | – | 4/2 | 2/4 | 4/3 | 6/2 | 7/1 | 3/1 | 1/4 | 2/3 | 4.9/3.4 | 1 | 2 | H | 45 | — | YES - GR. RDS. | 35 | A |
| NO | 5 | NO | 5 | 10 | — | — | 2 | 2 | 2 | 4 | 6 | 2 | 2 | 4 | 0.9 | 0 | 0 | H | 45 | — | YES-GR. RDS.-CP. | 35 | B |

(k) AFTER INSTALLING GROUND RODS BUT BEFORE COUNTERPOISES.

(l) PROTECTOR TUBES INSTALLED SPRING OF 1934 AND RING AND RINGS REMOVED.

(m) PROTECTOR TUBES INSTALLED ON ONE CIRCUIT SUMMER OF 1933 - RINGS AND HORNS REMOVED FROM THIS CIRCUIT.

(n) TOP AND MIDDLE PHASES ONLY; BOTTOM PHASE 10 UNITS.

(o) SINGLE AND DOUBLE CIRCUIT OUTAGES NOT SEGREGATED.

(p) 25 CYCLE LINE.

(q) BUILT FOR 132 KV., OPERATED AT 33 KV.

(r) ONE CIRCUIT WITH PROTECTOR TUBES - AND SECTIONALIZED AT MID-POINT - PROTECTOR TUBES INSTALLED SEPTEMBER 1935.

(s) PROTECTOR TUBES EVERY FIFTH TOWER.

(t) RINGS AND RINGS ONE CIRCUIT - SPOONS ON OTHER CIRCUIT.

(u) LINE 2AA AND CONTINUING 2A LINE INCLUDED TOGETHER AS 38.8 MILES.

(v) SOME LONGER SPACED UNITS IN USE.

(w) WOOD ARMS.

(x) AS REQUIRED TO REDUCE RESISTANCE TO 60 OHMS OR LESS.

(y) ON PART OF LINE ONLY.

(z) GROUND WIRES ON 67.3 MILES ONLY.

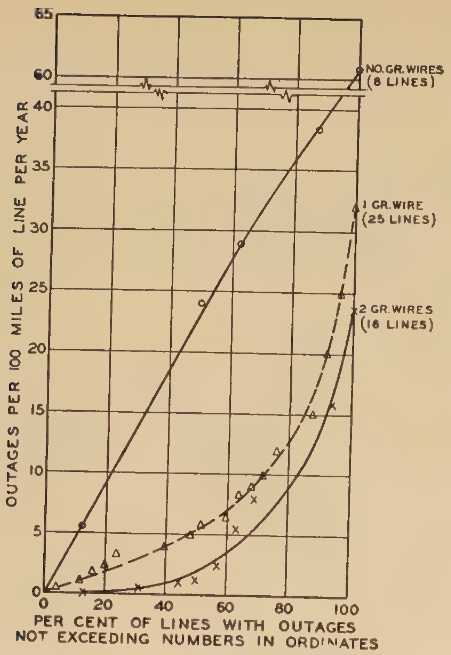


**Figure 16. Effect of ground wires on lightning outages of single-circuit lines**

of outages (from table III) is 1.40. While these figures are indicative of the benefit accruing from using a second ground wire it should be kept in mind that many of the two-ground-wire lines have been constructed with more insulation and other lightning resistant features than have generally been employed on some of the older single-circuit lines.

A clearer graphic picture of the benefits of the use of ground wires is shown in figure 16. On all single-circuit lines with and without ground wires, where the record is clear, it is shown that 50 per cent of the lines included here have outages not exceeding 24 for 100 miles with no ground wire, 5.5 with one ground wire, and 2.0 with two ground wires.

Considerable theory and discussions have been presented in the past on the desirability of locating the ground wire at a considerable height above the line conductors. In an attempt to obtain statistical data on this subject, the average line outages for 10 years, or the period reported, have been plotted against the height of ground wire above the top conductor. The record is shown in figure 17. While it appears that two lines, one with a ground wire 18.9 feet and the other 20 feet above the line conductor, have a practically perfect operating record, it should be pointed out, however, that both of these lines also have line insulation and clearance at the tower considerably higher than has been generally reported for other lines of the same voltage classification. With outages ranging from 0 to 61.0 per year where the ground wire heights range from 7 to 13 feet above the conductor, however, it would appear that there are other factors more important than the height of the ground wire above the conductor that control the outages.

### Single-Circuit and Two-Circuit Outages

A comparison of single- and double-circuit outages is given in figure 18. It will be noted that for 50 per cent of the two-circuit lines the double-circuit outages do not exceed about 1.0 and the single-circuit outages 4.0 per 100 miles of line per year. It thus appears that the double-circuit outages are 20 per cent of the total outages on two-circuit lines for 50 per cent of the cases. For 80 per cent of the lines, 32 per cent of the outages are double circuit. As the yearly outages increase, single- and double-circuit outages become nearly equal.

A comparison of single-circuit steel and wood lines is also shown graphically in this figure 18. Here wood does not show up to any particular advantage against steel.

### Tower Footing Resistance

The beneficial effect of tower footing resistance in reducing lightning outages has been presented both theoretically and from practical operating data previously. To throw some further light on this aspect of lightning protection, the pertinent data have been taken from table II and plotted against average tower footing resistance in figure 19. The trend to low outages with low resistance is quite marked here. The general conclusion that can be drawn from this curve is that if the line outages are to be kept to a low value, the tower footing resistance should be not in excess of 10 ohms per tower. It should be noted, however, that low tower footing resistance, or counterpoises, alone will not suffice, as shown by a few yearly outages from 5 to 22 even where the resistance is 10 ohms or less per tower.

### Local Lightning Severity

Any accurate comparison of the lightning performance of lines must of necessity take into account the lightning conditions under which the line is called upon to operate. An attempt to reduce lightning outages to a common basis would require a reasonably accurate evaluation of the lightning severity in the territory where the line is located. No easy way of doing this presents itself. However, columns 46 and 47 of table II indicate to some degree the severity of the lightning territory. The data in column 46 is the estimate of lightning severity given by the reporting companies. The figure in column 47 is the isokeraunic level taken from the 20-year average isokeraunic data as published by the United States Government. The lightning territory in this tabulation ranges from lightning storms of a density of 22 storms per year up to a maximum of 68 per year, that is, a ratio of over three to one. No attempt has been made to evaluate line outages taking into account this variation of lightning density as it is felt that the data as a

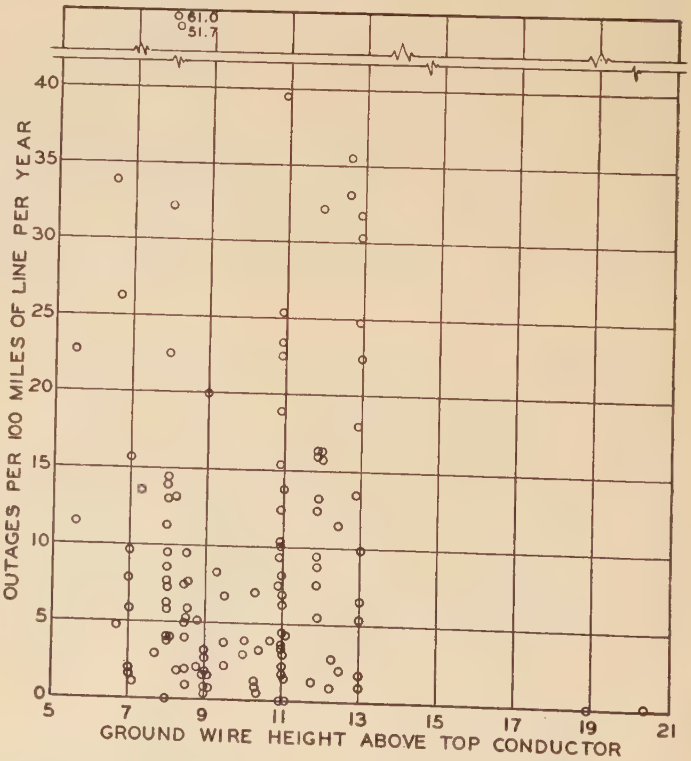


**Figure 17. Effect of ground wire height on line outages. Steel-tower lines only**

whole do not lend themselves readily to this type of analysis. The conclusions drawn from such an analysis might be so susceptible to error that no quantitative correlation has been attempted. In general, however, it is quite noticeable that the higher figures for line outages per year are associated, as might be expected, with the higher lightning density of the territory where the line is located.

## INSULATORS AND LINE CLEARANCE

All insulators are, of course, of the suspension type and range in size from $4^3/_4$-inch spacing to $6^1/_2$-inch. The number of insulators used in suspension strings ranges from 6 to 8 for wood structures and from 6 to 11 for steel structures in the 110-kv class to 9 to 11 for wood and 8 to 12 in the 132-kv class. This is exclusive of the long spaced ($6^1/_2$-inch) unit, used on a few lines.

Where wood structures are used, it will be noted that there is no general tendency to decrease the number of insulators used. However, in some of the 110-kv wood-pole lines seven units are used, although there is little apparent indication that this number of units was used with the intention of utilizing the wood as normal-frequency voltage insulation.

In the matter of clearances at towers between the conductor and the tower structure, it will be noted that the clearance ranges from a minimum of 31 inches for 110-kv lines up to a maximum of 67 inches at 45 degrees and 30 degrees conductor swing, respectively. For the 132-kv lines the range of clearances is from 37 inches to 66 inches at conductor swings in the order of 50 degrees.

In general it is not apparent from an analysis of the line outage data that the amount of insulation provided in the insulator string itself has a great deal of bearing on the performance of the line under lightning conditions. In other words, any attempt to overinsulate a line beyond normal requirements does not appear to have much influence on its lightning outage record.

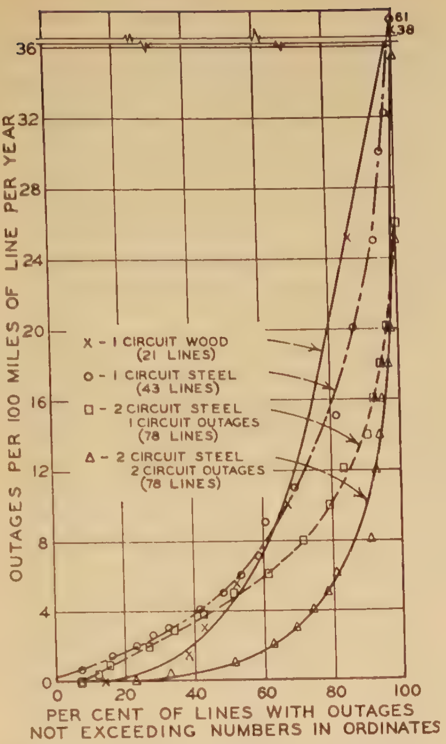


**Figure 18. Lightning outages on transmission lines. Single- and double-circuit lines with wood or steel structures**

## HEIGHTS OF CONDUCTORS

The opinion has sometimes been expressed in the past that a line which was built low to the ground was more immune from lightning troubles. The data presented in table II, however, fail to bear out this contention. For example, a comparison of the operating record of the lines of company 4, where the height of conductors is 46 feet, with the record of company 8, where the height of conductors is 100 feet, shows on an average higher outages for the line built closer to the ground. A comparison of other lines given in the table gives the same type of conflicting data. From this record it might be concluded that whatever factor the height of the line above ground may have in influencing the lightning outages, it is frequently submerged in other factors of line construction.

**Table III. Effect of Ground Wires on Lightning Outages of 165–110 Kv Transmission Lines**

| | Number of Lines | Line Miles | Outages per 100 Miles of Line per Year |
|---|---|---|---|
| **No-ground-wire lines** | | | |
| Single-circuit wood | 5 | 250.9 | 30.2 |
| Single-circuit steel | 3 | 290.8 | 29.8 |
| Total | | 541.7 | 30.0 |
| **One-ground-wire lines** | | | |
| Single-circuit wood | 1 | 68.3 | 0.44 |
| Single-circuit steel | 27 | 1,086.1 | 9.8 |
| Double-circuit wood | 51 | 2,236.3 | 7.1/4.2 |
| Double-circuit steel | | | |
| **Two-ground-wire lines** | | | |
| Single-circuit wood | 12 | 940.0 | 5.1 |
| Single-circuit steel | 4 | 241.9 | 7.0 |
| Double-circuit wood | 18 | 969.9 | 5.2/3.5 |
| Double-circuit steel | | | |

## ARCING PROTECTION AND PROLONGED OUTAGES

In an attempt to determine whether high-voltage transmission systems in general are subject to prolonged outages, the data in columns 44 and 45 of table II have been listed. Analysis of these data shows that in general burned-down conductors and prolonged outages, except in the case of one company, are relatively rare and are confined almost entirely to those circuits where the most modern type of arcing protection is absent. Most of the cases reported are on lines having insulator strings equipped with arcing horns on the line side only, or where no arcing protection at all is applied to the insulator strings. A summary of the record shows the following:

| | Rings and Horns or Rings and Rings | Line Rings Only | No Protection |
|---|---|---|---|
| Burned-down conductors | 1 | 44 | 31 |
| Prolonged outages | 9 | 85 | 27 |
| Miles of line | 1,962 | 2,022 | 2,613 |

A study of the relay and breaker times to clear faults (columns 29, 30, and 31 of table II) does not clearly indicate that moderately fast clearing of the fault will mitigate line troubles unless some effective arcing protection is applied to the insulator assemblies. It should be pointed out, however, that the relay and breaker operating times in table II are those presumably in use at the present time, so that troubles reported in many cases may have occurred before means were taken to speed up relay and breaker time.

## SATISFACTORY PERFORMANCE OF LINES AND IMPROVEMENTS CONSIDERED

In answer to the question as to whether the lightning outage performance of the lines as given by each company was satisfactory or not and whether improvements were being considered to better that performance, it will be noted from columns

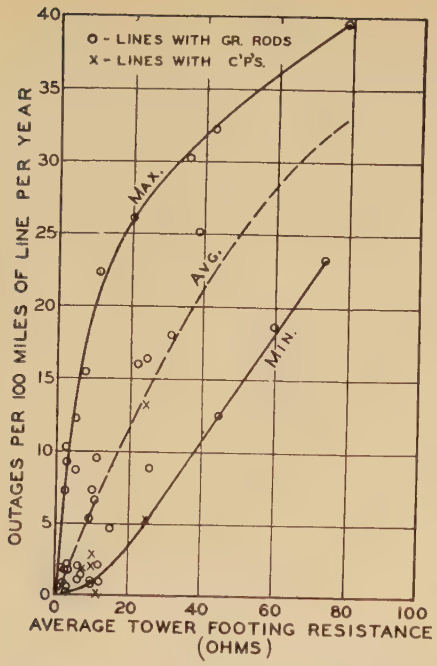


**Figure 19. Effect of tower footing resistance on line outages for steel-tower ground-wire lines**

48 and 49 in table II that in the large majority of cases, companies reported the operation was considered satisfactory. It should be pointed out, however, as mentioned by one reporting company, that while the outage record of some lines is not considered particularly low, the particular operating conditions do not require the high grade of line performance which might be required under some other operating conditions. For example, where two-circuit lines are in use, a high single-circuit outage record is not highly objectionable. On the other hand, where the outage record is high for double-circuit outages, or for single-circuit outages on single-circuit lines, the condition is entirely different. Again, where lines are operated in parallel with other lines between the source of power and load, or serve as a tie between two sources of power, the outage performance of such lines under lightning conditions may not be as exacting as in the case of lines which are the only source of power supply to important loads.

It will be noted that the general types of improvement being considered comprise lowering tower footing resistance, either by ground rods or counterpoises, use of protector tubes, and, as reported by one company, fast-reclosing high-speed breakers.

## Conclusions

In presenting such a voluminous mass of data as given in table II and attempting to correlate and analyze the operating records of some 150 transmission lines it is not hoped more than to touch on the salient points. The following conclusions, from the analysis made, however, seem to be justified:

1. Overhead ground wires are a very effective means of reducing line outages.

2. Placing the ground wire at excessively great heights above the line conductor does not seem to be justified.

3. Low tower footing resistance is necessary to reduce line outages due to lightning (provided lightning discharge devices such as protector tubes are not used). Values in the order of 10 ohms or less are suggested as desirable.

4. The conductor height above ground (tower height) does not appear to be an important contributing factor in affecting line outages.

5. Considerable benefit should be possible in improving the outage performance of lines by the judicious use of wood as insulation against lightning.

6. Double-circuiting a line is an effective method of reducing service outages as shown by the low ratio of double-circuit outages to total outages on such lines.

7. Effective arcing protection on insulator assemblies is desirable to reduce line troubles. Horns on the line side only do not supply such protection.

8. The generally considered means of bettering the lightning performance of lines in the 110- to 165-kv class as reported here are (1) lowering tower footing resistance, by ground rods or counterpoises, (2) protector tubes, and (3) fast-reclosing high-speed breakers.

9. The committee welcomes discussions from any of the companies who have contributed data on which this paper has been based, particularly as they may throw any further light on special features of their line construction which have affected the line performance. Comments will also be appreciated on features not possible to cover fully in answers to the committee questionnaire, or not fully covered in this presentation and discussion.

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## Discussion

**E. R. Whitehead** (Duquesne Light Company, Pittsburgh, Pa.): This paper is of special interest and value to me at this time because the company with which I am associated has just completed a rather detailed study of the lightning performance of its 66-kv transmission ring. While there are minor variations in the tower configuration a sufficiently representative one consists of a double-circuit vertical arrangement as in figure 1 of the paper. Top and bottom phases are separated 18 feet between circuits, while the middle phases are separated 22 feet. The vertical separation is 8 feet between top and middle phases and 7 feet between middle and bottom phases. The single ground wire is 7 feet above the top conductor. Six units are used in suspension and seven units for dead end. Air clearance is generally $3^{1}/_{2}$ feet.

Lightning tripouts in outages per hundred tower mile years vary from a low of 3.97 to a high of 56.8. The two sections to which these figures apply lie on opposite sides of the city, and in the past it has been assumed without question that the great differences were attributable to "preferred storm paths."

In an effort to verify this assumption, several exposed 22-kv subtransmission lines without ground wires were chosen adjacent to these 66-kv line sections and tripouts from lightning compiled in the same terms over a five-year period. The figures are 61 and 70, respectively. It is apparent that "preferred storm paths" will not account for the great difference in performance.

Since the study was primarily directed toward the improvement of poorly performing line sections, the worst of these, 28.36 miles in length, was selected together with an adjacent section 15.08 miles long and 32 towers chosen at random for ground resistance measurements. Here again it had been tacitly assumed that the poor performance could be explained by the storm frequency and very high ground resistances. The belief in the presence of high tower footing resistances arose from an earlier survey which included measurements of ground rods disconnected from the towers.

Footing resistances from 1.6 to 78 ohms were measured, the average being 16 ohms. Calculations based upon this average resistance and upon perfect ground-wire shielding gave an over-all flashover figure of 4.25 per cent. The actual flashovers for this section average 11 per year, requiring the absurd total of 260 strokes to the tower line per year. As previously stated, exposed 22-kv lines in the same general area had an outage record of only 70 per hundred miles per year. From this sample, taking into account the relative heights of the 66-kv and 22-kv lines, it has been estimated that the actual number of strokes to the 28.36-mile 66-kv line section was approximately 32.

The first step toward more accurate analysis was the construction of a tower-footing-resistance distribution table from the field data and the recalculation of the over-all flashover percentage. This calculation included midspan flashover for midspan stroke tower flashover for midspan stroke, and tower flashover for tower stroke. The result in this case was 12.45 per cent. It is clear that average ground resistance is not at all a suitable datum upon which to base estimates of line performance, nor can one easily correlate the data in the present paper with calculations. Using this percentage and assuming perfect shielding, the required number of strokes to the line is 88. This figure is still more than double a reasonable number.

The second refinement was an attempt to evaluate the effect of the electrostatically induced potential on the line wire. As has been pointed out,[1] the effect is to lower the tower-top potential necessary to cause insulation flashover, and the per cent flashovers will increase correspondingly.

An approximate method was derived to include this effect by considering a cloud height of 1,000 feet, rectangular bound charge of 2,000 feet length, a lightning current of $^1/_{20}$ microsecond, and discharge increments of one microsecond each. At the point of stroke the maximum induced voltage is proportional to the stroke current, and a fixed constant of proportionality may be added to the tower footing resistance when solving for the current required to cause flashover. The result of this approximation was to increase the per cent flashovers to a value of 15.0.

With such a small increase attributable to the effect of induced voltage on the line wire, it was felt that the assumption of perfect shielding was invalid.

If $X$ is the fraction of total strokes which strike a line conductor, then we may define the "shielding factor" as $(1 - X)$ and the equation governing flashovers is

$$Xn + (1 - X)\,Pn = F$$

where

$n$ = total strokes to tower line
$P$ = per cent flashovers for complete shielding
$F$ = flashovers

Inserting

$P = 0.15 \qquad F = 11 \qquad n = 32$

in this equation, there is

$$0.85X + 0.15 = \frac{11}{32} = 0.344$$
$$0.85X = 0.194$$
$$X = 0.228$$

Shielding factor $= 1 - X = 0.772$, a value which has been deduced as the shielding efficiency of the Glenlyn-Roanoke 132-kv line which has a single ground wire.[2]

In order to test this analysis further, a number of tower-footing-resistance measurements were made on the line sections having the best performance. All values were under ten ohms, and since the distribution curve was taken in ten-ohm steps, this value was used to compute comparative performance of these sections.

The results were:

| Line | Average Flashovers per Year | |
|---|---|---|
| | Actual | Calculated |
| Colfax-North | 3.5 | 3.70 |
| Colfax-Pine Creek | 1.4 | 1.67 |
| Pine Creek-North | 3.0 | 2.29 |
| B. I.-Woodville | 1.7 | 2.01 |
| Woodville-Dravosburg | 1.5 | 2.23 |

With one exception, the calculated faults are in excess of the actual as would be expected when Megger resistance values are used instead of the surge values which are somewhat lower. Moreover, some subnormal insulation and clearances may exist on this line.

It appears that the effect of induced line voltage would be negligible on most of the lines whose performance is reported in the paper, but if shielding were generally of the order of 0.75 for single-ground-wire lines it should be evidenced by components independent of ground resistance in the curves of figure 19. Because of the absence of this component, one is tempted to conclude that practically complete shielding exists for the great majority of lines listed.

A partial explanation of this apparent disagreement may lie in the fact that while the ground wire on our lines is 7 feet above the top conductor on the drawing, it has been found as low as $3^1/_2$ feet above the top conductor in numerous instances because of the substitution of suspension towers for strain towers. The exact proportion of these cases is unknown at this writing.

For the transmission engineer who contemplates reconstruction of old lines to improve lightning performance the question of shielding and its numerical measure is of paramount importance, and the writer will welcome any comment which the authors of the paper may make with regard to this point.

## REFERENCES

1. Discussion of PROTECTOR TUBE APPLICATION AND PERFORMANCE ON 132-KV TRANSMISSION LINES—II, **Philip Sporn and I. W. Gross, by L. V. Bewley.** ELECTRICAL ENGINEERING, September 1938.

2. Discussion of LIGHTNING INVESTIGATION ON TRANSMISSION LINES—V, **Lewis and Foust, by S. M. Zubair.** ELECTRICAL ENGINEERING, March 1936, page 277.

**S. K. Waldorf** (Pennsylvania Water and Power Company, Baltimore, Md.): In item 26*A* of table II of the paper are given data on the Safe Harbor-Perryville Line of the Pennsylvania Water and Power Company. The single case of burned-down conductor and prolonged outage on this line was due to sleet, and not to lightning. An additional year of operation without outage of this line has been obtained since the data were submitted to the committee, making four years in all.

In the committee's report an attempt has been made to evaluate the benefits to be derived from various factors which enter into lightning protection, such as overhead ground wires, insulation level, etc. As the committee has pointed out, it is very difficult to determine the influence of any one factor upon performance. For instance, in figure 17 of the paper, showing the effect of ground wire height on line outages, the points are widely scattered, indicating that there are other factors which are probably more important than this one item. However, in figure 19, showing the effect of tower footing resistance on line outages, the behavior of lines having counterpoise is shown to be definitely superior to those having ground rods. It should be noted that these data do not indicate any special benefits due to counterpoise other than as a means for reducing tower footing resistance, but they do indicate that tower footing resistance is a powerful factor in lightning protection.

In figures 10 to 15, inclusive, are given a number of general arrangements for counterpoise. The arrangement which has been most effective on the system of the Pennsylvania Water and Power Company has been a graded installation scheme where the number and length of counterpoise conductors have been varied to suit individual tower grounding conditions. It was on the Safe Harbor-Perryville 132-kv line that the first extensive use of this scheme of counterpoise installation was made by the Pennsylvania Water and Power Company. On this line as many as eight conductors in parallel were used as a counterpoise system connected to towers having high footing resistances initially. In such cases four geometrically and electrically parallel conductors were installed along the right-of-way on each side of a tower. Based on experiments in the field, later practice has been to limit counterpoise conductors to six in parallel, three conductors on each side of a tower. Where it has been necessary to install three parallel conductors, they have in many cases been extended to the adjacent towers and the wire used in this way rather than in adding a fourth wire.

Figure 16 indicates a superiority of two overhead ground wires over one overhead ground wire. During the past lightning season, the Pennsylvania Water and Power Company has had the opportunity of comparing the operation of two 69-kv lines of very nearly identical characteristics except as regards the number of overhead ground wires and their position. These two lines are the Holtwood-York line, 22.8 miles long, with two overhead ground wires 10 feet above the topmost line conductors at all towers, and the Holtwood-Coatesville line, 29.4 miles long, with a single overhead ground wire $3^1/_2$ feet above the topmost line conductors at strain towers and $7^1/_2$ feet above at suspension towers. Before the installation of counterpoise, the average tower footing resistances were within one ohm of each other at 133 ohms and after the installation were again within the same limit, but at 9 ohms. The Holtwood-York line has been operating for three years since improvements were made, and has had an average of 2.9 outages per 100 miles of line per year. The Holtwood-Coatesville line has operated for only one year since improvements were made, with one outage occurring, making an average of 3.4 outages per 100 miles of line per year. Although the limited period of operating experience makes it still too early to draw any conclusions, the similar behavior of these two lines indicates that the shielding provided by a single overhead ground wire may be better than heretofore has been believed to be the case.

Examination of the data on the relative frequency of single-circuit and double-circuit outages shows that on those lines having a large number of double-circuit outages, the high values of tower footing resistance are probably the principal cause of the poor performance.

The committee has not found any great dependence of performance upon insulation level. Perhaps a partial explanation of this conclusion is that the insulation level varied no more than about in the ratio of 5 to 3 whereas the footing resistances varied as much as 20 to 1. Variations in the latter factor probably obscured any effects of variation in the former. Lewis and Foust pointed out in 1934 that flashover of shielded lines occurs only when the product of tower footing resistance and tower lightning current exceeds the insulation level of the line. Experience in ensuing years has shown this to be essentially correct, which establishes the close relationship between line insulation and lightning performance.

When tower footing resistances are high, no reasonable amount of insulation will protect against flashover. Data from lines in this classification will show no effects of line insulation upon performance. Analysis of some data available on 19 110-kv steel-tower lines, 787 miles long; 5 132-kv steel-tower lines, 263 miles long; and 9 110-kv wood-pole lines, 460 miles long, all with overhead ground wires, other than those given in the paper, shows a more definite benefit due to increased line insulation. In the 110-kv class, steel lines having six insulator units in strings showed an average of 40 interruptions per 100 miles of circuit per year, those with seven units showed 10.9 interruptions, those with eight units had 5 interruptions, and those with nine units showed 2.2 interruptions. On 132-kv steel lines, those lines with 9 insulator units in strings experienced 21.1 outages per 100 miles of circuit per year, those with 11 units showed 2.8 outages, and those with 12 units, 2.1 outages. Thus, this study showed a decided benefit due to increased insulation on steel-tower lines, but the benefit is probably more apparent than real, because no account was taken of variations in footing resistance when classifying the data. With wooden construction, the investigation showed that on 110-kv lines the outages per 100 miles of line per year were 3.7 with six insulator units, 7.3 with seven units, and 7.2 with eight units. Apparently the effect of the wooden insulation in series with the porcelain masks the effect of the increased number of insulator units, in addition to any uncertainties introduced due to neglecting the effect of tower footing resistances.

In conclusion 7 it is stated that arcing protection on insulator assemblies is desirable to reduce line troubles. It would seem more logical on lines having overhead ground wires to use the money for improving grounding conditions, rather than for arcing protection, and thus greatly reduce the number of flashovers. With modern high-speed switches, severe burning of conductors is rare.

Line 3*A* in table II shows a considerable number of double-circuit outages but no single-circuit outages over a period of ten years. This behavior is most unusual and some reasonable explanation for it would be valuable. In this report the committee has tried to segregate the effect of the various means employed to reduce lightning outages on transmission lines. In making such a segregation the results of necessity must be more or less inconsistent as the three factors; overhead ground wires, insulation, and tower footing resistances, are interdependent. Each one is dependent on the other two for its proper functioning in this scheme of protection.

**E. W. Knapp** (Shawinigan Water and Power Company, Montreal, Que., Canada): The committee responsible for the collection and preparation of the data incorporated in this paper are to be congratulated on the concise and clear manner in which the wealth of information has been presented. A study of the general situation brings to mind a few additional points which might prove of interest.

The system which I wish to discuss consists of two double-circuit steel-tower lines 86 miles long on the same right-of-way. The lines are operated at 110 kv, and have seven units of insulation. Lines *A* and *B* have two overhead ground wires while lines *C* and *D* have no overhead ground wires. An analysis of the lightning outages during the past ten years reveals the data shown in table I of this discussion, based on outages per 100 miles of line per year.

Table I. Lightning Outages, 1929–1938, Inclusive

| Single Line Outages | | | | | Double Line Outages | | |
|---|---|---|---|---|---|---|---|
| Overhead Ground Wire | | No Overhead Ground Wire | | Total | Overhead Ground Wire | No Overhead Ground Wire | Total |
| A | B | C | D | | A/B | C/D | |
| 0.93 | 0.82 | 0.23 | 9.3 | 11.2 | 2.8 | 4.3 | 7.1 |
| 8.3% | 7.3% | 2.0% | 82.4% | 100% | 40% | 60% | 100% |

There are three points of special interest:

1. The line farthest away from the overhead ground wires suffered the most lightning outages.
2. The two lines without overhead ground wires suffered the greater number of double line outages.
3. There was a greater percentage of double line outages on the lines with overhead ground wires, although the total outages were considerably lower.

**Philip Sporn** and **I. W. Gross:** Mr. Whitehead's method of analysis to determine lightning outages on existing lines is quite interesting, and if experience continues to bear out the close relation between actual and calculated values, it should be a method decidedly helpful in predetermining the lightning performance of new lines before they are actually constructed and placed in service.

As Mr. Whitehead points out, the matter of shielding, that is, keeping lightning off the phase wires, is most important since it is quite apparent that no matter how low the tower footing resistance is, it will not be effective in preventing flashover if the stroke terminates on the line wires rather than the ground conductor. This subject well warrants further study and confirming field data.

Mr. Waldorf has drawn the conclusion (apparently based on figure 19) that "the behavior of lines having counterpoise is shown to be definitely superior to those having ground rods." While this appears to be a reasonable deduction, if the data of figure 19 only are considered, it will be noted in referring to table II that only four of the lines out of some 150 have counterpoises throughout 30 per cent of their length or over. Mr. Waldorf's 26*A* line, which has counterpoise for 93 per cent of its length, he reports as having no outages in four years. It will be noted that this line has an average structure ground resistance of 11.4 ohms. On the other hand, line 21*E*, which has counterpoise for 38 per cent of its length, with an average structure footing resistance of 10 ohms, shows 9.8 average outages per hundred miles of line per year. Line 15*I* having ground rods only for 56 per cent of its length has an average structure resistance of 10 ohms and a yearly outage record of 0.9 per hundred miles of line. While it may be true that a reduction of tower footing resistance to a given level by counterpoises will result in less line outages than a similar reduction by the use of ground rods, it does not appear from the data which have been presented in table II that such a conclusion is wholly justified.

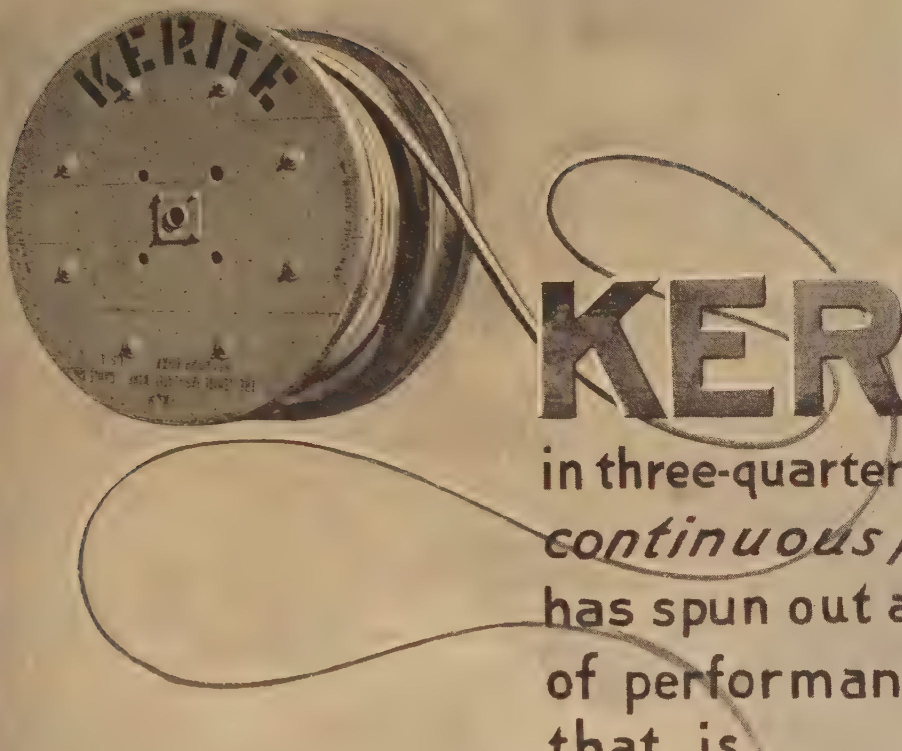
The specific cases mentioned by Mr. Waldorf, one where two ground wires were used and one where only one was used indicating the same relative order of line performance, he has interpreted as indicating that one single overhead ground wire may be giving far better shielding than generally believed. The summarized data in the paper tend to lend weight to this point of view, although as pointed out in the paper, the data in many cases are not complete enough to show definitely the influence of other factors such as number of insulators, line spacing, lightning territory, etc.

The citation by Mr. Waldorf of outages on steel-tower lines as affected by the number of insulator units tends to show some benefit by increasing the number of units from six to nine. This, of course, is an increase in insulation of 50 per cent between extreme limits of insulation. As he has clearly pointed out, it is necessary to take into consideration all of the lightning protective features of the line before definite conclusions can be drawn on the merits of any one influencing factor. An attempt to analyze data of this kind, as well as that given in table II of the paper, requires a rather detailed study of many of the line characteristics before any hard and fast conclusions can be drawn.

Mr. Waldorf suggests the improvement of ground resistance on a line with overhead ground wires, in place of supplying arcing protection, and we are in thorough agreement with this statement where modern, high-speed breakers clear the fault; and, in fact, in recent lines on our own system, we have eliminated the arcing protection where high-speed breakers are used. Where slow line relaying, however, still exists or is a necessity as a result of system operation, arcing protection may still be desirable.

In referring to line 3*A* in table II, we are inclined to believe that the absence of single-circuit outages in the reported figure of 35.5 outages per hundred miles of line per year is due to the absence of a breakdown of the total outages for the ten-year period. The figures are reported as received, but, as pointed out by Mr. Waldorf, they may well be questioned.

In conclusion, it is not expected in attempting to analyze the mass of data such as given in table II that all the various factors can be definitely evaluated. It was the hope of the committee in submitting this report to collect sufficient authentic data on a large group of lines in the country so that careful analysis might show the trends in the construction and the general experience in the operation of such lines under lightning conditions.



**KERITE**
in three-quarters of a century of *continuous production*, has spun out a record of performance that is *unequalled* in the history of insulated wires and cables

DAYS KERITE

THE KERITE INSULATED WIRE & CABLE COMPANY INC
NEW YORK CHICAGO SAN FRANCISCO

# Industrial Notes

**Capacity of U. S. Water Power Plants.**—The total installed capacity of water power plants of 100 or more horsepower in the United States and outlying territories on January 1, 1939, was 18,093,726 horsepower, according to a recent announcement of the Federal Power Commission. The United States total was 17,948,906 horsepower, an increase of 4 per cent over the previous year. The report shows that 88 per cent was installed in electric utility plants and the balance in industrial and miscellaneous plants.

**Large Turbine Contracts Awarded.**—The Federal government has recently awarded contracts amounting to $1,843,200 to the Allis-Chalmers Mfg. Co. for power machinery, including 4 turbines of 103,000-hp capacity, to be installed at Shasta Dam of the Central Valley (Cal.) reclamation project. A contract for two smaller turbines was awarded to James Leffel & Co. of Springfield, Ohio, for $68,055.

**Okonite Promotions.**—Charles M. Kirkland was recently elected secretary of The Okonite Co., at Passaic, N. J., and the Okonite-Callender Cable Co., Paterson, N. J. He was formerly engaged in sales work with the company in the Chicago territory. F. J. Dahleiden has been appointed manager of the newly established Okonite district office in the National Building, 1404 E. 9th St., Cleveland. He was formerly sales engineer in the Chicago territory.

**Power Sales Increase in N. J.**—Improvement in industrial conditions in the first four months of this year, as compared with the first four months of 1938 is indicated by the increased consumption of electric power and gas fuel by manufacturing and other business enterprises in the New Jersey territory served by Public Service Electric & Gas Co. Electric power sales increased 16.26 per cent and sales of gas for industrial uses were up 13.5 per cent. The company furnishes electric power to 94 per cent of all industries in its territory.

**Increased Appliance Sales.**—Household washer shipments in April continued their advance over 1938, aggregating 116,199, or 22.11 per cent more than the total, 95,158, reported for the same month a year ago. It was the sixth consecutive month showing an increase above the same period a year before. April ironer shipments totalled 9,047 compared to 7,111 a year ago, an increase of 27.23 per cent. Ironers shipped in the four months were 36,878 compared to 37,628 in the same period of 1938.

**Cramer Company Moves to Connecticut.**—The R. W. Cramer Co., Inc., formerly located at 67 Irving Pl., New York City, has moved into its new plant located in Centerbrook, Conn. A New York sales office in charge of R. C. Heyl, a vice-president of the company, will be retained at the old location. This company has been for many years the United States distributors of Sauter time switches, a Swiss product. In the new plant they will also manufacture the Cramer running time meters and a new complete and diversified line of electric timers.

**Walker Electrical Co. Appointment.**—T. J. Fleischer, formerly connected with the Crouse-Hinds Co., has been appointed general sales manager of the electrical manufacturing division of the Walker Electrical Co., Atlanta, Ga. The company is erecting a new plant in Atlanta's northside section, for the manufacture of a complete line of outlet boxes and accessories.

**New Plant for Carboloy.**—The new $750,000 plant and general offices of the Carboloy Co., Inc., at Detroit, Mich., a General Electric subsidiary, was formally opened on June 1 for the manufacture of masonry drills for drilling holes in all non-metallic construction materials and other cemented carbide products. This new structure, the largest cemented carbide plant in the United States, embraces a total area of 121,750 square feet.

# Trade Literature

**Varnished Insulation.**—Bulletin, 28 pp. Describes varnished cambric and tape of various types; varnished insulating silk, paper, canvas and duck, tubing, fiberglas, transformer leads, etc. Irvington Varnish & Insulator Co., Irvington, N. J.

**Tong Test Ammeter.**—Bulletin 400, 6 pp. Describes the various types of Crompton Tong Test ammeters for instant a-c or d-c current measurements on bare or insulated conductors without breaking the circuit. Columbia Electric Mfg. Co., 4525 Hamilton Ave., N.E., Cleveland, O.

**Measuring Bridge.**—Bulletin 620. Describes the "Dwarf" measuring bridge for measuring resistance in the field, factory and laboratory. Advantages include a wide range, simple manipulation, high sensitivity and light weight. Herman H. Sticht & Co., 27 Park Pl., New York, N. Y.

**Insulated Cables.**—Bulletin 2007 A, 8 pp. Describes the advantages and applications of "Okolite" insulated cables for high voltage circuits; includes comparative curves of the operating efficiency, greater load carrying ability and moisture-resistance. Additional data is given on installation methods, tests and available designs. The Okonite Co., Passaic, N. J.

**World's Fair Automatic Substation.**—A bulletin (No. 3905) issued by the I-T-E Circuit Breaker Co., 19th & Hamilton Sts., Philadelphia, Pa., describes the new, completely automatic World's Fair substation of the Interborough Subway System, New York City. Included is a colored map of transportation routes, both rail and road from the metropolitan area to the World's Fair; also an invitation to all Fair visitors to participate in inspection trips to the new substation.

**Plastics.**—Bulletin 1518 B, 16 pp., "A Business Man's Guide to Modern Plastic Materials." Profusely illustrated, this bulletin covers the wide applications of Bakelite molding and other materials throughout all industries, including the electrical field. Bakelite Corp., 247 Park Ave., New York.

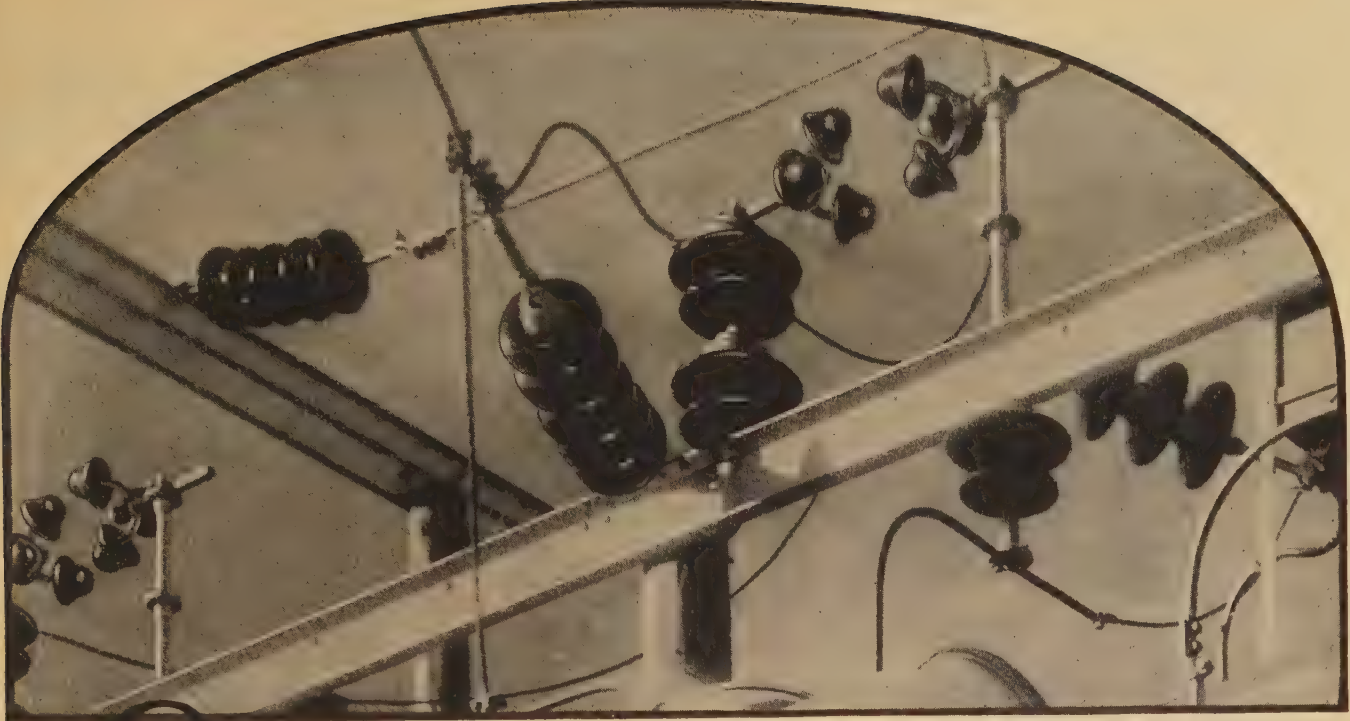
**Wood Preservation Equipment.**—Bulletin 1834, 32 pp., "Machinery for Wood Preservation." Outlines the history of wood preservation, types of preservatives used in modern treatment, methods and processes, and types of machinery used. Allis-Chalmers Mfg. Co., Milwaukee, Wis.

**Concrete for Buildings.**—Bulletin, 40 pp., "Concrete for Industrial Buildings and Garages." Contains a comprehensive description of structural layouts and details, mechanical installations, and alterations in concrete buildings. Numerous drawings, sketches and photographs are included. Portland Cement Association, 33 W. Grand Ave., Chicago, Ill.

**Recording Voltmeter.**—Bulletin 538. Describes a new, round-chart, portable recording voltmeter, built especially for survey work. A self-contained instrument enclosed in a waterproof case, it is designed for indoor or outdoor service and equipped for adjustable mounting legs for pole or wall mounting. The Bristol Co., Waterbury, Conn.

**Motor Maintenance Equipment.**—Catalog, 84 pp. Describes a complete line of portable equipment for maintenance of commutators and slip rings; motor repair equipment; variable speed transmissions; cleaning equipment; soldering tools; testing and recording devices, etc. Sections are devoted to care of electrical equipment of various types, electrical terms, wire tables, etc. Ideal Commutator Dresser Co., Sycamore, Ill.

**Testing Equipment.**—Catalog AE11-a. Describes a new "Hipot" insulator and bushing tester for testing by the voltage gradient method and which indicates location as well as extent of faults. The improved device employs a more sensitive instrument, has a changeover switch for high and low voltage, special prongs and leather carrying case. Catalog AE11-b covers new applications of the "Hipot" Potential Indicator, which includes furnishing a continuous line to ground voltage indication; use as an indicator of synchronism or to synchronize two or more lines; for operating relays for signal purposes; and line to ground fault indication or relaying. Roller-Smith Co., Bethlehem, Pa.



# One Lightning Stroke

## MIGHT BUY MANY CONTROL GAPS

DID YOU ever figure up what lightning costs each year? If so, you know that the bill is usually a staggering one. Just a single stroke might cost thousands of dollars, should it damage apparatus of high rating. And to this bill for labor and materials would be added the loss of revenue and good will from a service interruption. Costly, yes, but you now have a device which may strike "lightning" from your expense ledger altogether—the O-B control gap. Fast as lightning itself, eliminating dangerous over-voltages by permitting unrestricted flow of surge current after gap flashover, adjustable to the voltage, time and polarity of the protected equipment, and performing satisfactorily in any weather, O-B control gaps provide *positive protection* against lightning and other over-voltage surges. Instead of paying for lightning repairs, why not buy these inexpensive gaps. You could probably equip all of the vulnerable spots of a station for what a single stroke would cost!

*Five sizes of O-B control gaps are available, for protecting equipment from 33 to 161 kv.*

*Lightning Protection at Lightning Speed*

**OHIO BRASS**
MANSFIELD OHIO, U. S. A.
Canadian Ohio Brass Co., Ltd., Niagara Falls, Ont., Canada

2066-H

IN ONE *Self Contained* INSTRUMENT

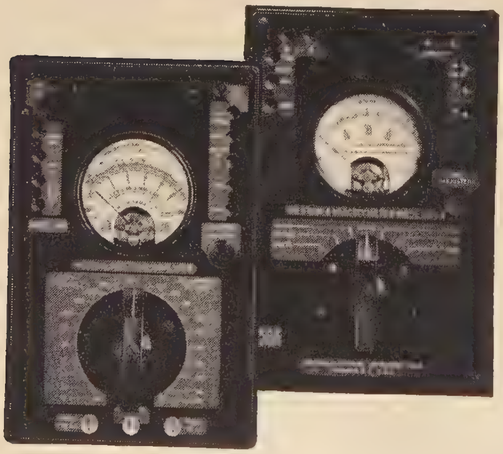
10
D. C. VOLTAGE RANGES
sensitivity 20,000 ohms per volt—1.5 to 1500 volts

10
A. C. VOLTAGE RANGES
sensitivity 1,000 ohms per volt—1.5 to 1500 volts

12
D. C. CURRENT RANGES
readings from 1 microampere to 15 amperes

10
DECIBEL RANGES
measurements from —18 DB to +58 DB

Here's an instrument that quickly pays for itself in any plant... because of the wide variety of jobs it will do. When not busy on trouble-shooting, it can be used for the inspection of purchased parts... for check-ups on plant equipment... for standardization studies or research work. It fits the assembly line, too; especially where runs are short, and circuits subject to change. And many other test requirements are fully met by this flexible, multi-range instrument... keeping it active... *earning*... throughout every working day. » » » Complete information on this Model 765 and other *equally flexible* WESTON multi-range instruments is available in bulletin form. Write to Weston Electrical Instrument Corporation, 644 Frelinghuysen Avenue, Newark, New Jersey.



Among other WESTON multi-range instruments are the Model 665 Volt-Ohm-Milliammeter... Model 763 Ohmmeter with resistance spread 1 ohm to 300 megohms (6 ranges)... Model 663 Volt-Ohmmeter... and Model 764 Capacity Meter covering measurements from .00005 to 100 microfarads.

WESTON
*Instruments*

# Thrills

## ...for you and your family at the New York World's Fair!

### WHEN YOU COME, BE SURE TO VISIT THE ROEBLING EXHIBIT!

**"I WANT YOU TO SEE THIS, JACK.** It's that Roebling Passenger Tramway I was talking to you about. Somebody used his head when he put in these blueprints so engineers can study the construction details."

TO YOU and your family . . . a hearty invitation to visit the Roebling Exhibit at the New York World's Fair!

No matter what your business activity . . . engineering, contracting, mining, railroading, manufacturing, building management or what-not . . . you will find that this Roebling Exhibit is designed specifically to interest *you*—to help make *your* visit instructive and keenly enjoyable.

Action every moment! Mining, construction, dredging and other industrial operations in full swing! All in miniature . . . with excavating, hoisting, and conveying equipment incredibly exact in detail. Even the tiny wire ropes and cables are exact duplicates of their full-size counterparts!

So come . . . you and your family. We will give you a royal welcome. And remember . . . we are in the Metals Building, directly in front of the Trylon and Perisphere.

JOHN A ROEBLING'S SONS COMPANY, TRENTON, N. J.

## ROEBLING

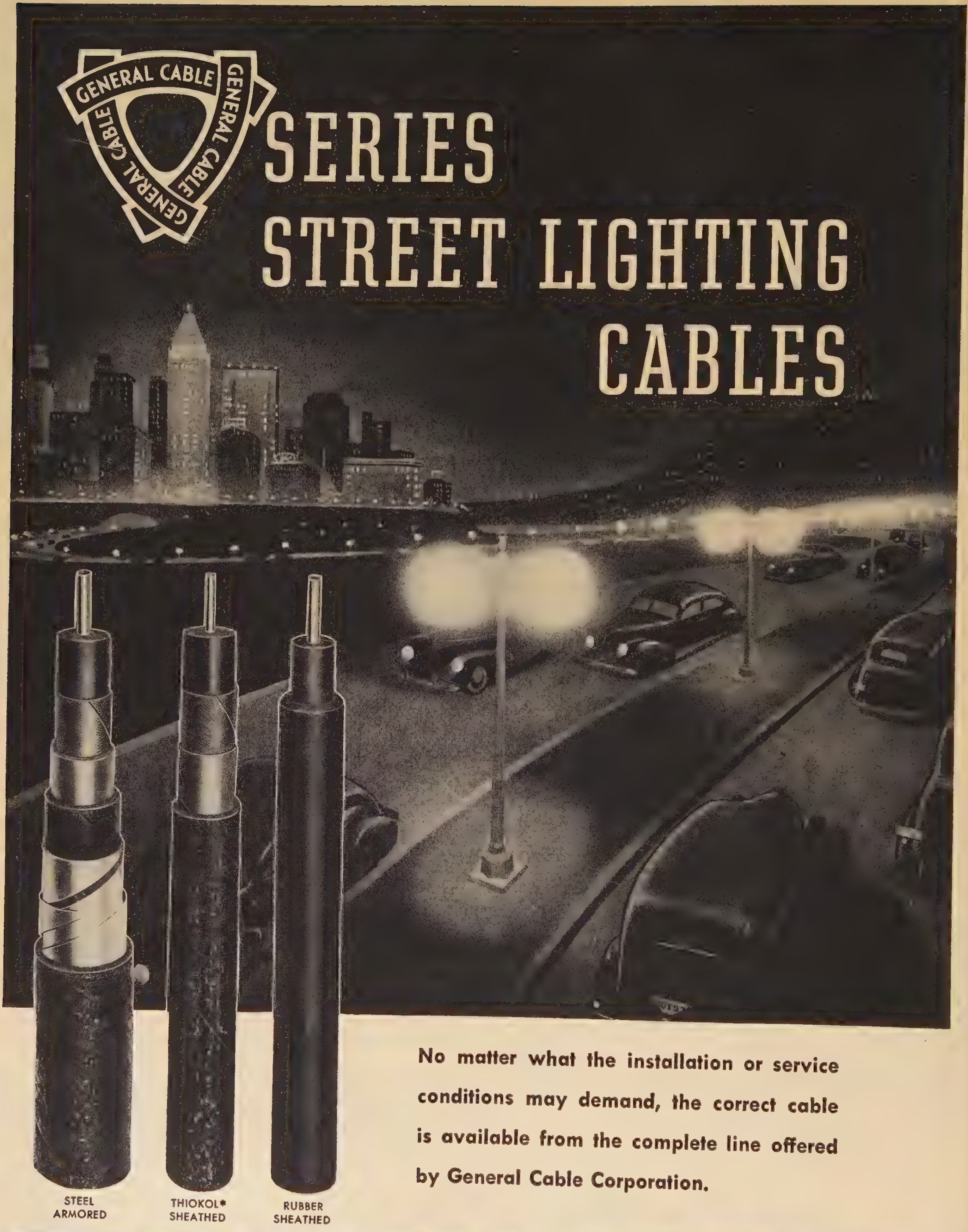
WIRE ROPE & FITTINGS • ELECTRIC WIRE &
CABLE • FLAT WIRE • WOVEN WIRE FABRICS •
WELDING WIRE • OTHER WIRES & WIRE PRODUCTS

**"THAT, MY DEAR,** is the world's largest dredge, the Crest. I've seen her—and this replica sure looks natural. Why, it's identical with the original, down to the last boom line and hoisting rope!"

**"THIS WILL INTEREST YOU, JOHNNY** . . . a whole village in miniature. See, there's a school, a church, a fire house, some stores—even a water tower and a railroad station. And look . . . here comes the train!"

**"WHILE MARY AND JOHNNY ARE RESTING,** suppose and I look over this interesting exhibit of Roel Products. There are more of them in the other rotu at the opposite end of the exhibit."

# SERIES STREET LIGHTING CABLES



No matter what the installation or service conditions may demand, the correct cable is available from the complete line offered by General Cable Corporation.

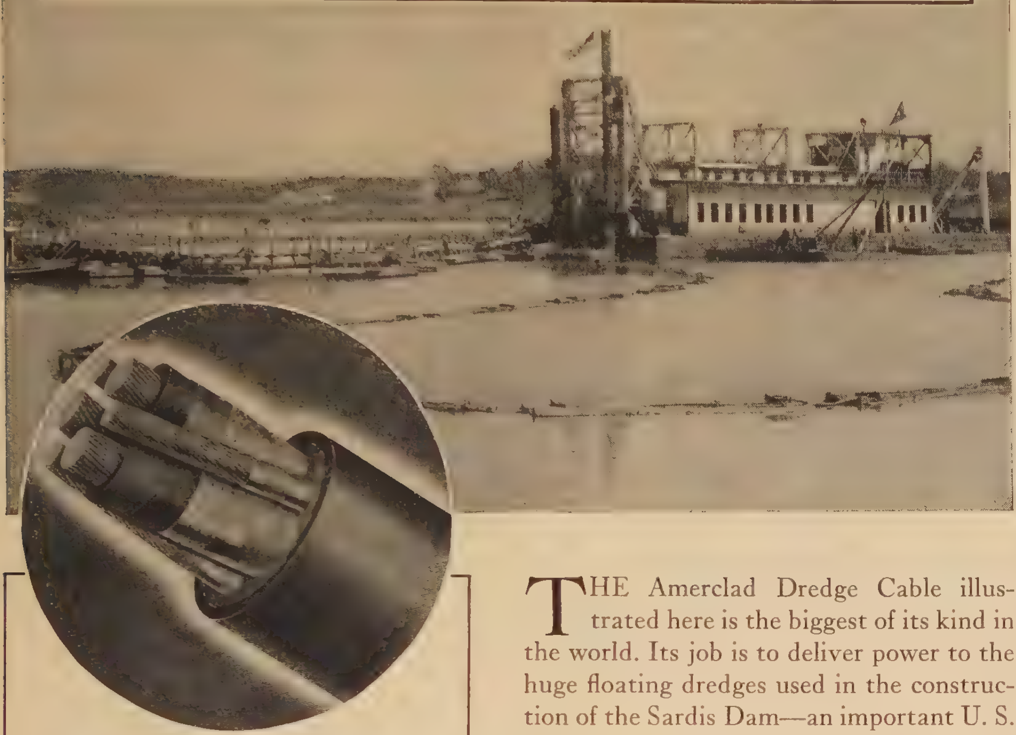
*Trade-Mark Thiokol Corporation

GENERAL CABLE

**General Cable Corporation Sales Offices:** ATLANTA • BOSTON • BUFFALO • CHICAGO • CINCINNATI • CLEVELAND • DALLAS • DETROIT
KANSAS CITY (MO.) • LOS ANGELES • NEW YORK • PHILADELPHIA • PITTSBURGH • ROME (N.Y.) • ST. LOUIS • SAN FRANCISCO • SEATTLE • WASHINGTON (D.C.)

# IN THE "BIG LEAGUE"... OR IN THE "BUSHES"

*You'll find Amerclad Cords and Cables Doing the Important Jobs*



ONE-FOURTH ACTUAL SIZE

THIS AMERCLAD CABLE, rated at 13,200 volts, contains three insulated conductors, each 500,000 c.m., and three ground wires, each No. 4/0 A.W.G. flexible copper strand. It weighs nearly 18 pounds per foot and has an outer diameter of 4½". Each of the insulated conductors is electrically shielded by a braid of tinned copper wires. Between the rubber insulation and copper braid, in intimate contact with both, is a fabric tape specially treated to provide a semi-conducting layer.

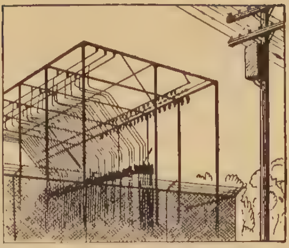
**AMERCLAD**
***All-Rubber***
**CORDS & CABLES**

THE Amerclad Dredge Cable illustrated here is the biggest of its kind in the world. Its job is to deliver power to the huge floating dredges used in the construction of the Sardis Dam—an important U. S. Government Flood Control Project.

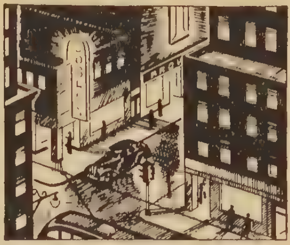
Today all jobs are important, whether big or little. And all along the line you will find Amerclad Cords and Cables doing big and little jobs efficiently and economically.

The outstanding features offered by Amerclad Cords and Cables are their rugged toughness, light weight and flexibility. An outer sheath of resilient "tire-tread" rubber protects the insulation from damage. Amerclad Cords and Cables are available in a wide range of types and constructions. Full details will be sent to you upon request.

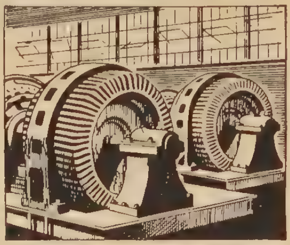
ADEQUATE WIRING SERVES AND SAVES



PAPER INSULATED CABLES

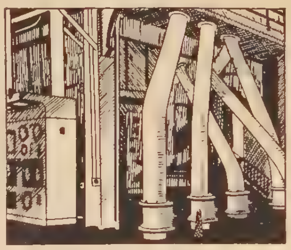


AMARINE NETWORK CABLES

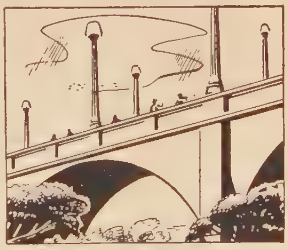


VARNISHED CAMBRIC CABLES

RELIANCE WEATHERPROOF WIRES



AMERBESTOS CABLES



PARKWAY CABLES

## AMERICAN STEEL & WIRE COMPANY

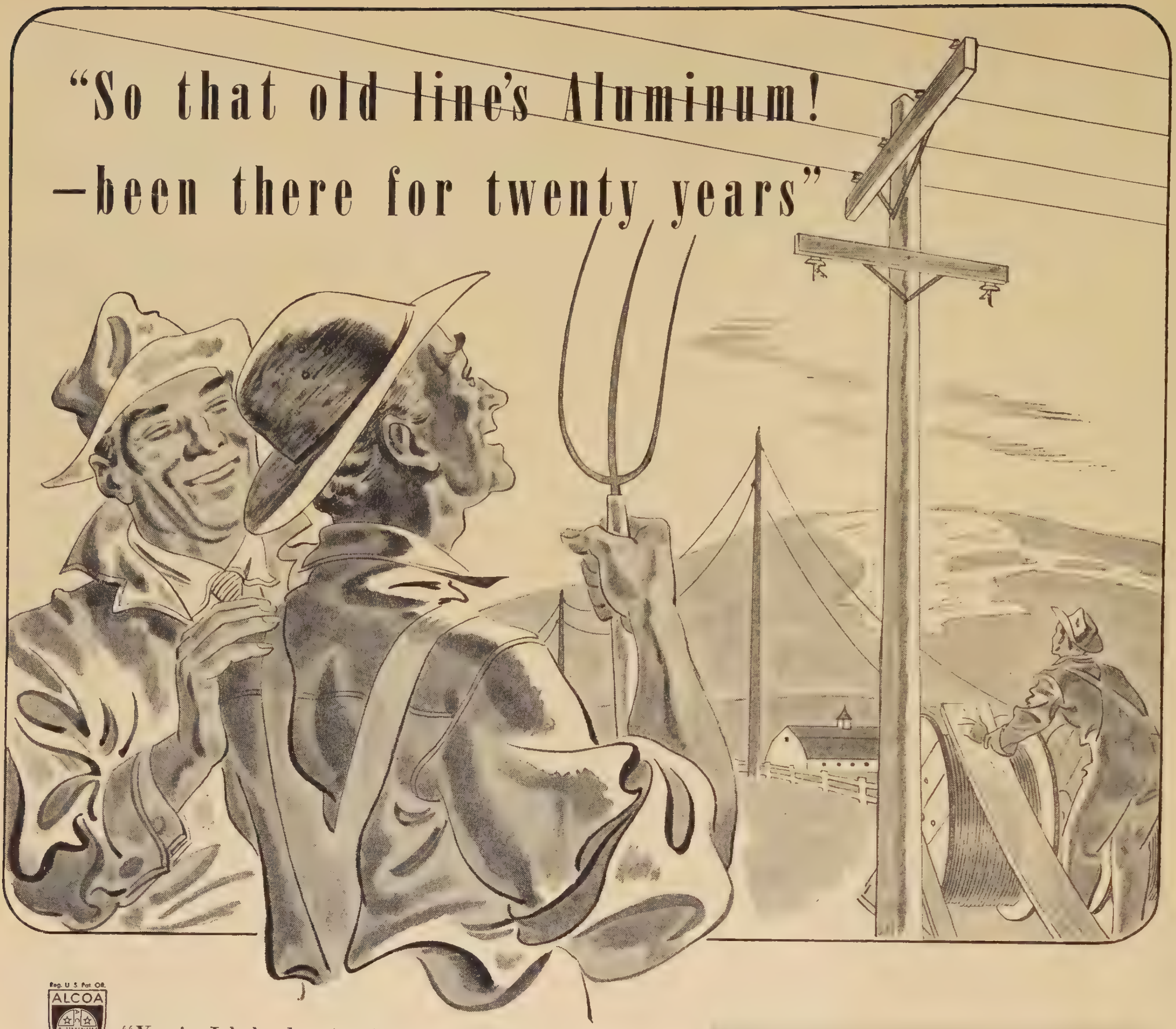
Cleveland, Chicago and New York

Columbia Steel Company, San Francisco, *Pacific Coast Distributors*

United States Steel Products Company, New York, *Export Distributors*

**UNITED STATES STEEL**

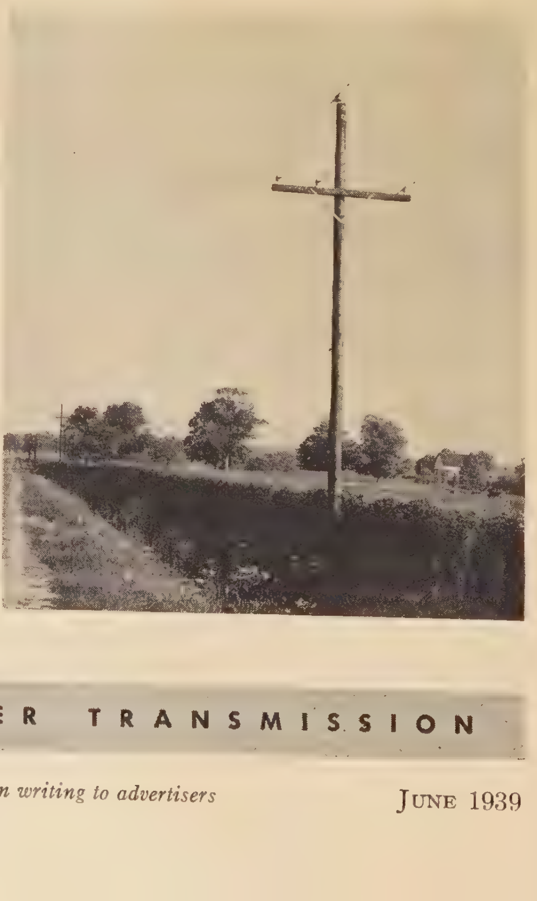
# "So that old line's Aluminum! —been there for twenty years"



"Yessir, I helped string it across your farm. The line's seen plenty of tough weather since then, too, and it's good for another twenty years. Your new line'll certainly be all right with the same stuff in it."

Trust the judgment of men who must face year 'round weather. A.C.S.R. lines have what it takes to stand up under adverse conditions — scorching summers, severe winters, sleet storms and high winds. This has been proved on thousands of miles of line, for more than 25 years.

A.C.S.R. has the high strength which permits long span construction with high safety factors. It provides the conductivity needed for future growth of load. Because it is highly resistant to corrosion, long life is assured. A.C.S.R. construction standards assure low building costs and a minimum of maintenance. ALUMINUM COMPANY OF AMERICA, 2149 Gulf Building, Pittsburgh, Pennsylvania.



# A·C·S·R

*Aluminum Cable Steel Reinforced*

FOR RURAL LINES AND POWER TRANSMISSION

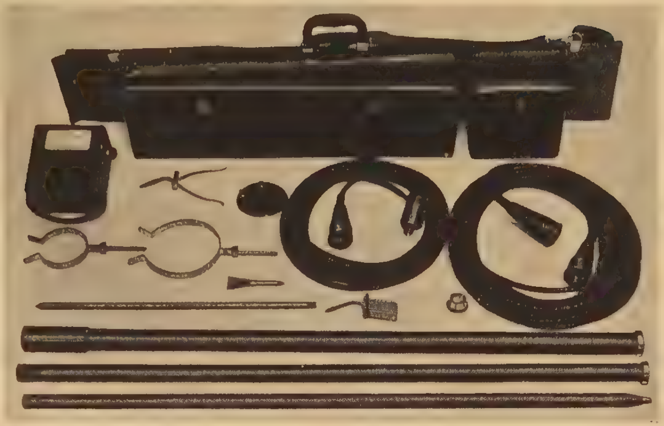
# *Roller-Smith Announces*

# 2 NEW DEVICES

### "HIPOT" INSULATOR AND BUSHING TESTER

The ideal equipment for testing insulators and transformer and oil circuit breaker bushings by the voltage gradient method. Range is 13,200 to 220,000 volts. Has many advantages over the power factor method, chief of which is indicating *location* as well as *extent* of fault.

New Catalog AE-11-a gives the details. Send for it. *Use the Coupon Below.*

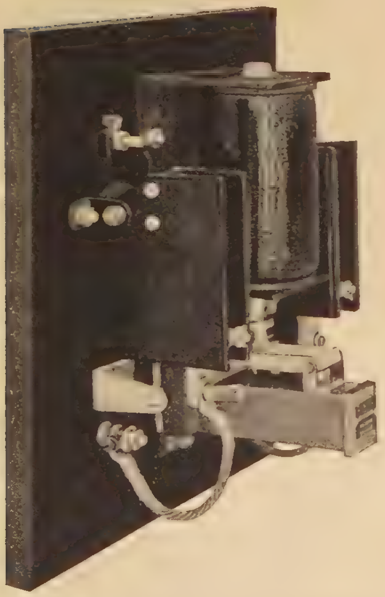


"HIPOT" INSULATOR AND BUSHING TESTER
With Accessories and Leather Case

### TYPE C CONTROL RELAY

The Type C control relay has many applications, chief of which is for insertion between the contacts of a control switch or push button and the operating solenoid of an electrically operated air or oil circuit breaker or other apparatus. Available for a-c or d-c. Trip-free or non-trip-free. Very rugged. No a-c hum. All parts accessible. Simple control wiring.

New Catalog AE-12 gives the details. Send for it. *Use the Coupon Below.*



TYPE C RELAY, TWO POLE, TRIP-FREE

ROLLER-SMITH COMPANY, Bethlehem, Pa.

Please send me the new Catalogs checked:

☐ Cat. AE-11-a on "Hipot" Insulator and Bushing Tester.
☐ Cat. AE-12 on Type C Control Relay.

Name ............................................................

Company ............................................................

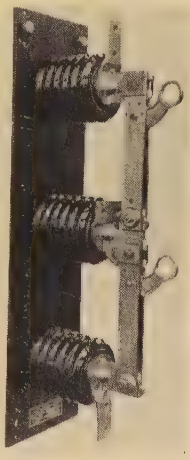
Address ............................................................

**ROLLER-SMITH COMPANY**
Electrical Measuring and Protective Apparatus

MAIN OFFICE AND WORKS BETHLEHEM, PA. U. S. A.

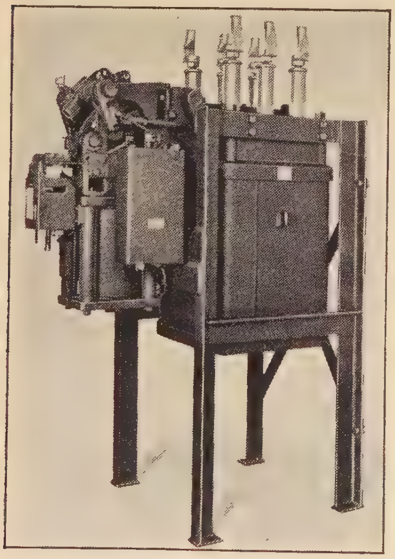
Sales Agencies in Principal Cities in United States and Canada

# New Products

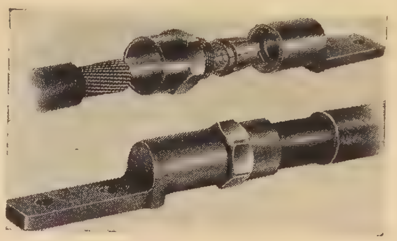


**Disconnecting Switch.**—In this new single pole, double blade, tandem throw, 15-kv, 600-ampere disconnecting switch, designed by the Delta-Star Electric Co., Chicago, the inside lock, combined with a common hinge and contact member at the center insulator unit, results in shorter blades and decrease in width of the current carrying parts. Both factors are important when switches are used in cubicles, cell structures and other restricted places, where available striking distance between the open switch blade and cell doors is limited. The tongue type contacts are of the line pressure type with full floating blades, plain or silvered as desired. At the hinge end of the blades are annular pressure rings. The steel base is equipped for mounting on either flat surface or $1^{1}/_{4}$-inch pipe frame.

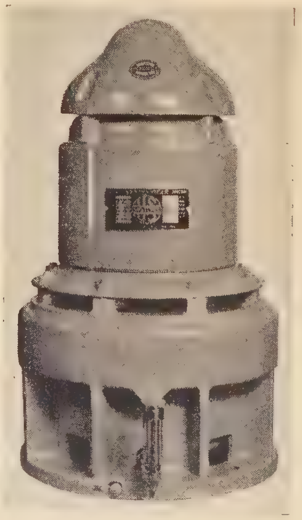
**Indoor Circuit Breaker.**—A new indoor oil circuit breaker, widely applicable to central station and industrial service, has been introduced by the Boston works of the Allis-Chalmers Mfg. Co. Designated as type KDZ-40, the breaker is of particular interest because its horizontal axis (a line drawn through the center of each pole) is perpendicular to the operating mechanism. This arrangement of the bushings eliminates the necessity of crossing the leads in certain applications of open and enclosed type switchboards. For the same reason, it is adaptable for replacing obsolete breakers of the same arrangement, as existing bus and feeder connections may be retained. The type KDZ-40 is equipped with "Ruptors" to give efficient interruption of short circuits along with low arc energy, low pressure and a minimum of oil deterioration. It is furnished for 600 and 1200 amperes at 15 kv and 2000 amperes at 7.5 kv; interrupting capacity rating 100,000 kva; arranged for flat surface mounting—in cells, switch-houses, cubicles, metal-clad switching equipments, etc.



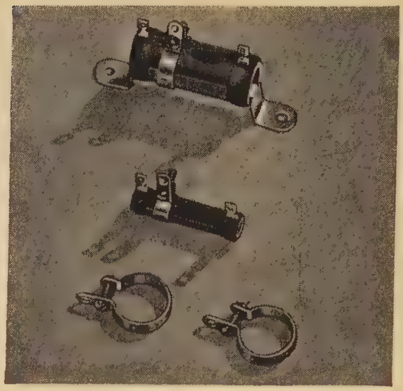
**Connectors.**—The Burndy Engineering Co., 459 East 133rd St., New York City, has announced a line of Hood-Nut connectors for use with rubber or compound insulated cables at points where these conductors are joined to other types of cable or to switches, cutouts, etc. In using these connectors, taping is done from the shroud of the nut to the rubber insulation of the cable. In this manner, moisture is prevented from entering between the insulation and the conductor, thereby prolonging the life of the insulation. The braid is peeled back beyond the tape to avoid "wick effect" which might draw up moisture beneath the tape. In addition to terminal type ZAK illustrated, Hood-Nut connectors are also furnished in the form of T-connectors, straight connectors and in special forms.



**Gear Motor.**—A new vertical "Syncrogear" unit type GDV, has been specially designed by U. S. Electrical Motors, Inc., Los Angeles, Calif., to meet conditions peculiar to vertical operation. The unit incorporates a small, geared, oil pump, which forces an ample oil supply to bearings, gears and pinions.



**Wire Wound Resistors.**—A new line of wire wound resistors has been made available by Consolidated Wire & Associated Corps., 548 So. Peoria St., Chicago, Ill. Four sizes of adjustable resistors are offered—10-watt, 25-watt, 50-watt, and 75-watt, of which the 10- and 25-watt sizes are shown with extra adjustable bands. Four sizes of wire wound fixed resistors are offered—5-watt, 10-watt, 20-watt, and 50-watt—to fill most requirements for receivers, transmitter, amplifier and industrial applications. Two mounting brackets are supplied on all but the 10-watt size in the adjustable resistors. All four sizes have two tab terminals. All four sizes of fixed resistance units have solder lugs and all but the 50-watt size have tinned copper leads as well.



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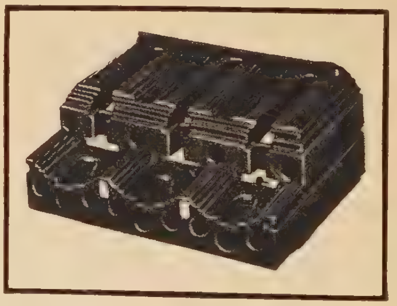

THIS "*Headache*" WAS QUICKLY CURED

At first glance this insulator looks terribly complicated. But in reality it simplifies the design of the product for which it is a part.

If you're wondering how to simplify your manufacturing and reduce assembly cost—look to Insulator Headquarters and let Universal plan a design with you. Universal "Dry Process" porcelain insulators have no comparable equal in quality, especially where dimension limitations are important. Samples to your specifications gladly supplied.

THE UNIVERSAL
CLAY PRODUCTS CO.
1360 E. FIRST ST.
SANDUSKY • OHIO

STANDARD OF THE WORLD
IRVINGTON INSULATION
TRADE MARK

# A Guarantee of Dependable Insulation

- Varnished Cambric and Tape
  Black or Yellow—Straight or Seamless Bias
- Varnished Canvas and Duck
- Varnished Silk
- Varnished Paper
- Varnished Fiberglas
- Varnished Tubing
- Slot Insulation
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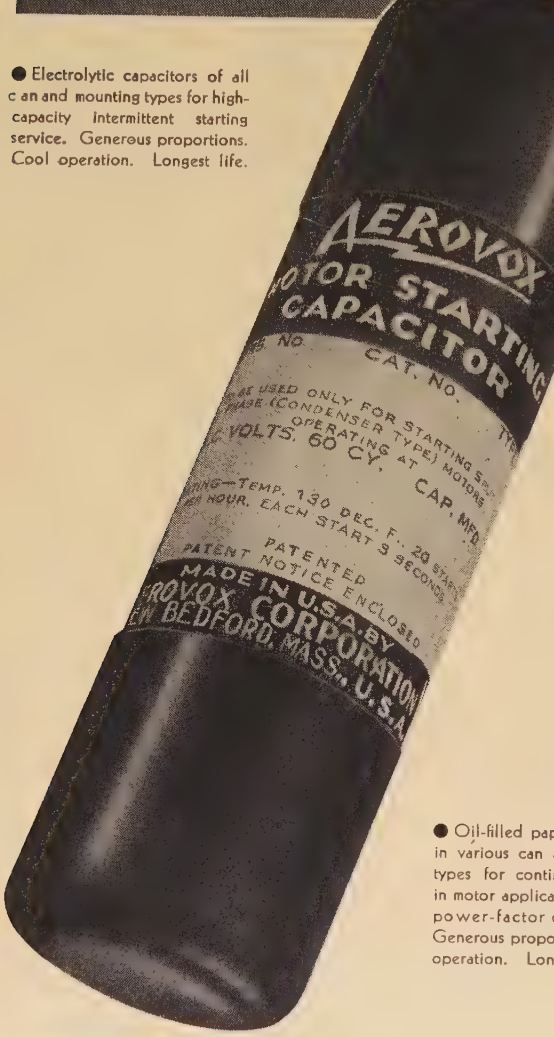

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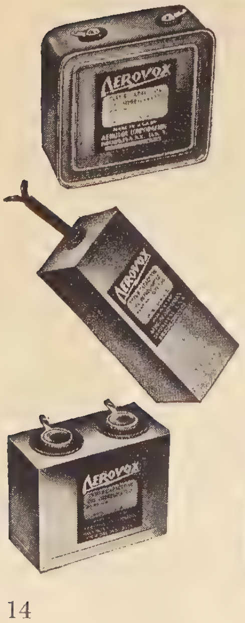

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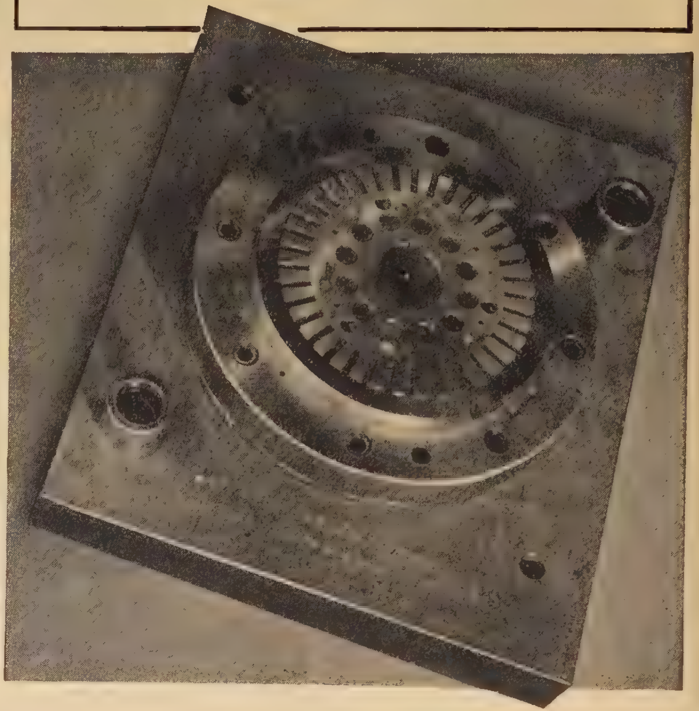

ARE your dies still sharp, accurate, and clean-punching after a tough day on the punch press?

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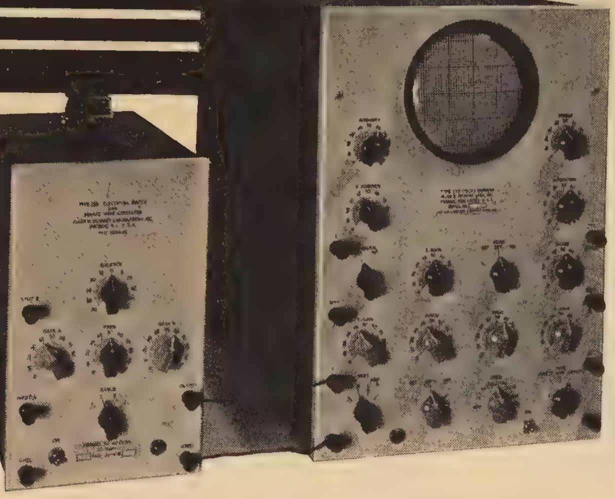
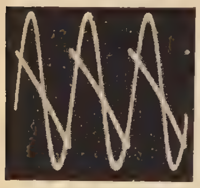
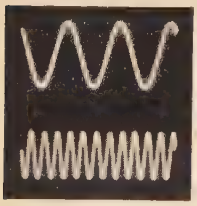


●For the comparison of voltage and current phase relationships in all power and communication circuits, the Du Mont Type 185 *Electronic Switch* used in conjunction with Type 175 *Cathode-Ray Oscillograph,* offers the only means available for the simultaneous observation and comparison of two phenomena *on a single* oscillograph screen.



Independence and freedom from interaction of the two channels are shown in this actual oscillogram. Illustrates ability of the Type 185 instrument to handle a saw-tooth and sinusoid at same time, and to make them appear on one oscillograph screen.



Actual photo showing comparison of two harmonically related signals on one oscillograph, using electronic switch. Patterns may be displaced as shown for individual observation.

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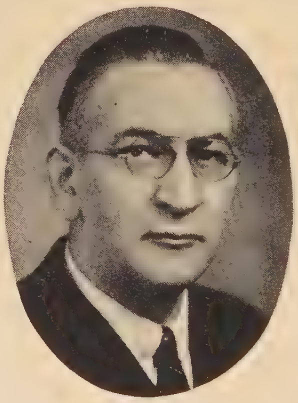

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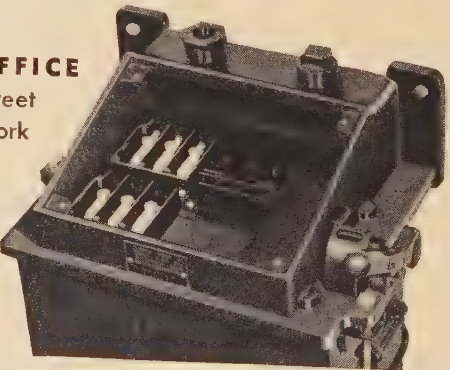

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**ROWAN CONTROL**

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# of the AIEE TRANSACTIONS

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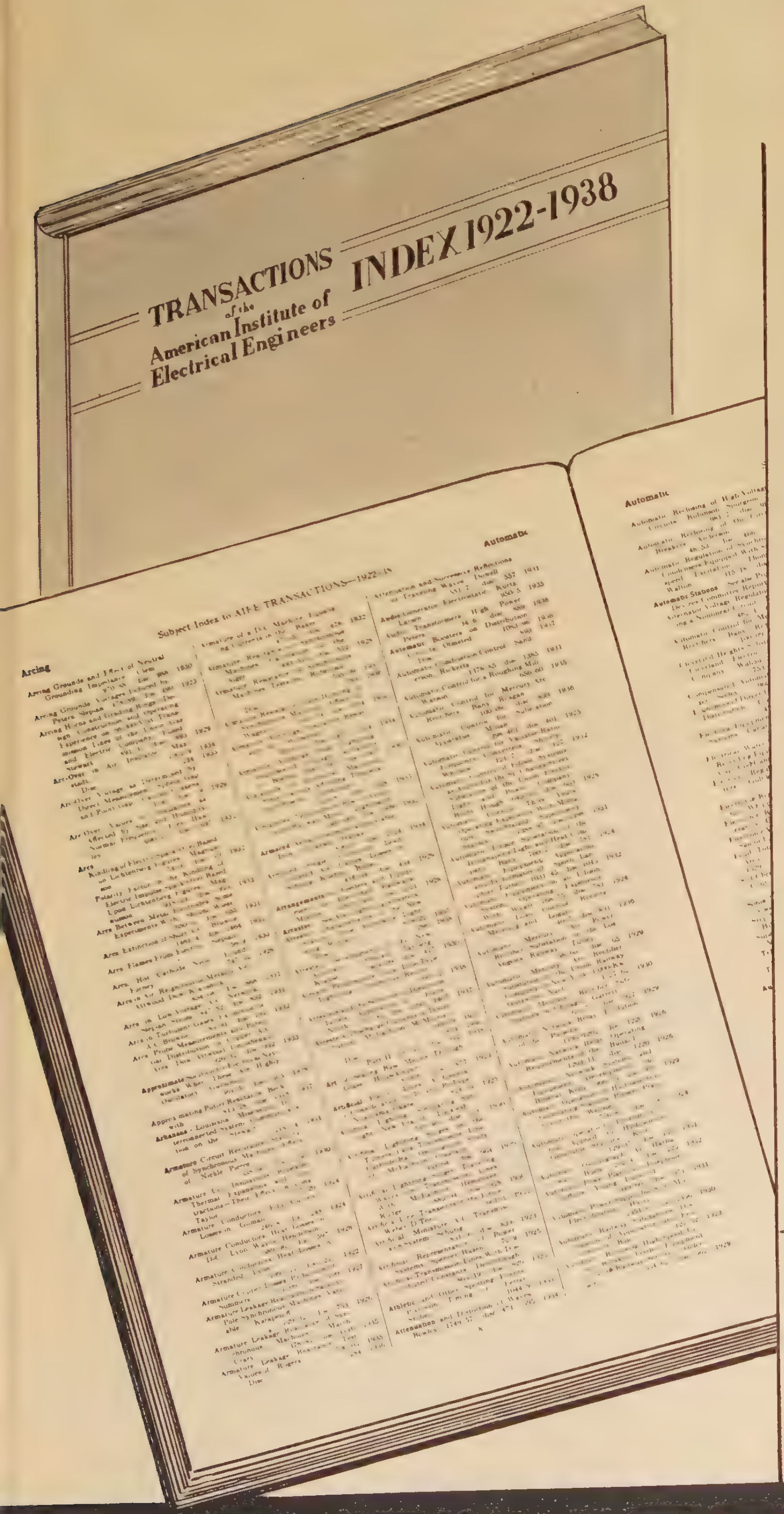

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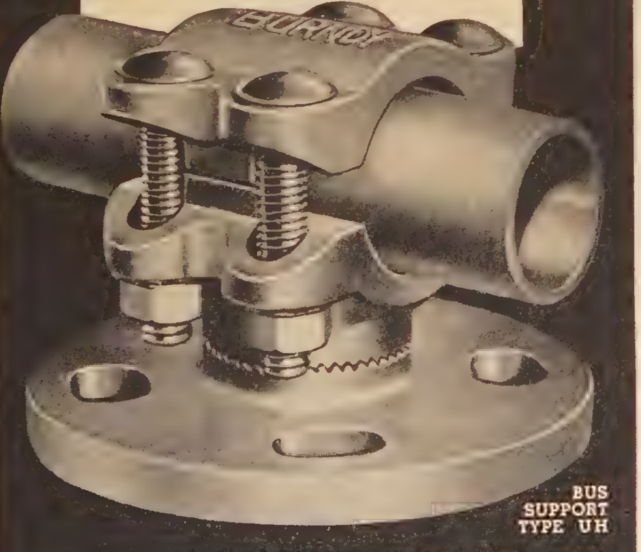

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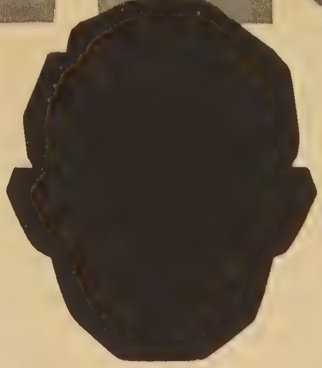

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Roebling's Sons Co., John A., Trenton, N. J.

*Varnishes*
General Electric Co., Bridgeport, Conn.
Mineralac Electric Co., Chicago

**INSULATORS, PORCELAIN**
General Electric Co., Schenectady, N. Y.
Ohio Brass Co., Mansfield, O.
Universal Clay Products Co., Sandusky, O.

**LIGHTING EQUIPMENT, OUTDOOR**
General Electric Co., Schenectady, N. Y.

**LIGHTNING ARRESTERS**
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**POLE LINE HARDWARE**
Malleable Iron Fittings Co., Branford, Conn.
Ohio Brass Co., Mansfield, O.

**POLE MOUNTS**
Malleable Iron Fittings Co., Branford, Conn.

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General Electric Co., Schenectady, N. Y.
General Radio Co., Cambridge, Mass.
Roller-Smith Co., Bethlehem, Pa.
Sola Electric Co., Chicago, Ill.

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General Electric Co., Schenectady, N. Y.
Guardian Elec. Mfg. Co., Chicago, Ill.
I-T-E Circuit Breaker Co., Philadelphia
Roller-Smith Co., Bethlehem, Pa.
Weston Elec. Instrument Corp., Newark, N. J.

**RESISTORS**
Aerovox Corp., New Bedford, Mass.
General Electric Co., Schenectady, N. Y.
General Radio Co., Cambridge, Mass.
International Resistance Co., Philadelphia
Ohmite Mfg. Co., Chicago

**RHEOSTATS, LABORATORY**
General Electric Co., Schenectady, N. Y.
International Resistance Co., Philadelphia
Ohmite Mfg. Co., Chicago

**SHEETS, ELECTRICAL**
Carnegie-Illinois Steel Corp., Pittsburgh

**SUB-STATIONS**
General Electric Co., Schenectady, N. Y.

**SURGE ABSORBERS**
Ferranti Electric, Inc., New York

**SWITCHBOARDS**
General Electric Co., Schenectady, N. Y.
I-T-E Circuit Breaker Co., Philadelphia
Roller-Smith Co., Bethlehem, Pa.

**SWITCHES, AUTOMATIC TIME**
General Electric Co., Schenectady, N. Y.
Mineralac Electric Co., Chicago

**SWITCHES, DISCONNECT**
General Electric Co., Schenectady, N. Y.
Roller-Smith Co., Bethlehem, Pa.

**SWITCHES, GENERATOR FIELD**
I-T-E Circuit Breaker Co., Philadelphia

**TOWERS, TRANSMISSION**
American Bridge Co., Pittsburgh

**TRANSFORMERS**
Acme Elec. & Mfg. Co., Cuba, N. Y.
Ferranti Electric, Inc., New York
General Electric Co., Schenectady, N. Y.
General Radio Co., Cambridge, Mass.
Sola Electric Co., Chicago

**TURBINE GENERATORS**
General Electric Co., Schenectady, N. Y.

**TURBINES**
General Electric Co., Schenectady, N. Y.

**WELDERS, ARC**
General Electric Co., Schenectady, N. Y.

**WELDING WIRE**
American Steel & Wire Co., Chicago
General Electric Co., Schenectady, N. Y.
Roebling's Sons Co., John A., Trenton, N. J.

**WIRES AND CABLES**

*Aluminum*
Aluminum Co. of America, Pittsburgh

*Armored Cable*
American Steel & Wire Co., Chicago
Crescent Ins. Wire & Cable Co., Trenton, N. J.
General Cable Corp., New York
General Electric Co., Schenectady, N. Y.
Kerite Ins. Wire & Cable Co., New York
Okonite Company, The, Passaic, N. J.
Roebling's Sons Co., John A., Trenton, N. J.

*Asbestos Covered*
American Steel & Wire Co., Chicago
General Cable Corp., New York
General Electric Co., Bridgeport, Conn.
Okonite Company, The, Passaic, N. J.
Roebling's Sons Co., John A., Trenton, N. J.

*Bare Copper*
American Steel & Wire Co., Chicago
Copperweld Steel Co., Glassport, Pa.
Crescent Ins. Wire & Cable Co., Trenton, N. J.
General Cable Corp., New York
Roebling's Sons Co., John A., Trenton, N. J.

*Bronze*
Copperweld Steel Co., Glassport, Pa.

*Copper Covered Steel*
American Steel & Wire Co., Chicago
Copperweld Steel Co., Glassport, Pa.
General Cable Corp., New York

*Flexible Cord*
American Steel & Wire Co., Chicago
Crescent Ins. Wire & Cable Co., Trenton, N. J.
General Cable Corp., New York
General Electric Co., Schenectady, N. Y.
Okonite Company, The, Passaic, N. J.
Roebling's Sons Co., John A., Trenton, N. J.

*Heavy Duty Cord*
American Steel & Wire Co., Chicago
Crescent Ins. Wire & Cable Co., Trenton, N. J.
General Cable Corp., New York
Okonite Company, The, Passaic, N. J.
Roebling's Sons Co., John A., Trenton, N. J.

*Lead Covered (Paper and Var. Cambric Ins.)*
American Steel & Wire Co., Chicago
Crescent Ins. Wire & Cable Co., Trenton, N. J.
General Cable Corp., New York
General Electric Co., Schenectady, N. Y.
Kerite Ins. Wire & Cable Co., New York
Okonite Company, The, Passaic, N. J.
Okonite-Callender Cable Co., Passaic, N. J.
Roebling's Sons Co., John A., Trenton, N. J.

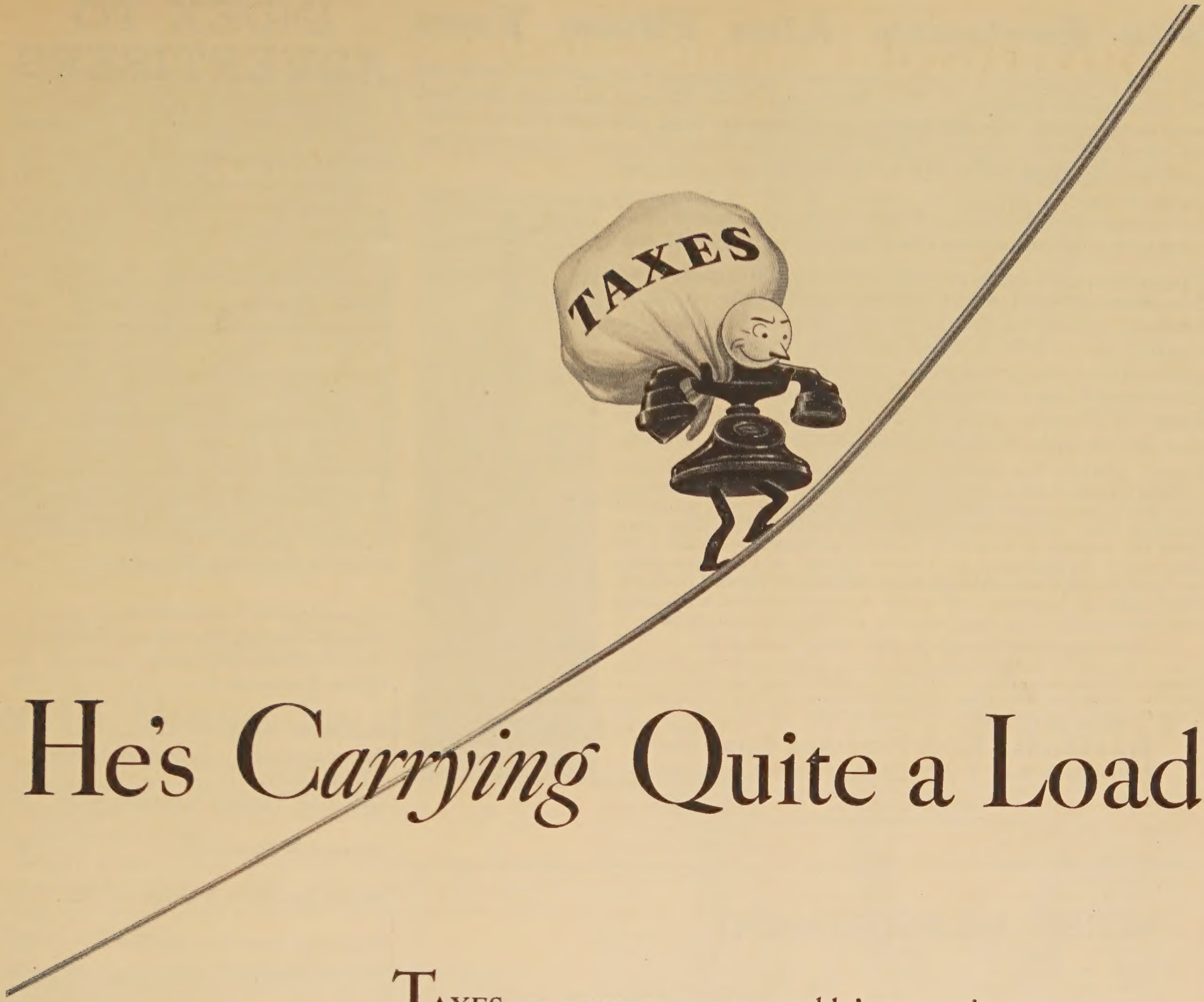
*Magnet*
American Steel & Wire Co., Chicago
Crescent Ins. Wire & Cable Co., Trenton, N. J.
General Cable Corp., New York
General Electric Co., Schenectady, N. Y.
Roebling's Sons Co., John A., Trenton, N. J.

*Rubber Insulated*
American Steel & Wire Co., Chicago
Crescent Ins. Wire & Cable Co., Trenton, N. J.
General Cable Corp., New York
General Electric Co., Schenectady, N. Y.
Kerite Ins. Wire & Cable Co., New York
Okonite Company, The, Passaic, N. J.
Roebling's Sons Co., John A., Trenton N. J.

*Tree Wire*
American Steel & Wire Co., Chicago
Crescent Ins. Wire & Cable Co., Trenton, N. J.
General Cable Corp., New York
Kerite Ins. Wire & Cable Co., New York
Okonite Company, The, Passaic, N. J.
Roebling's Sons Co., John A., Trenton, N. J.

*Weatherproof*
American Steel & Wire Co., Chicago
Crescent Ins. Wire & Cable Co., Trenton, N. J.
Copperweld Steel Co., Glassport, Pa.
General Cable Corp., New York
General Electric Co., Schenectady, N. Y.
Okonite Company, The, Passaic, N. J.
Roebling's Sons Co., John A., Trenton, N. J.

**X-RAY UNITS, INDUSTRIAL**
General Electric X-ray Corp., Chicago Ill.



He's *Carrying* Quite a Load

TAXES are necessary—you couldn't run a city, state or government without them. But they do mount up.

Fact is, a considerable part of the money you pay us for telephone service goes right out in taxes.

Bell System taxes for 1938 were $147,400,000—an increase of 56% in three years. In 1938 taxes were:

Equal to about $550 a year per employee

Equal to $9.50 per telephone in the Bell System

Equal to $7.54 per share of A. T. & T. common stock

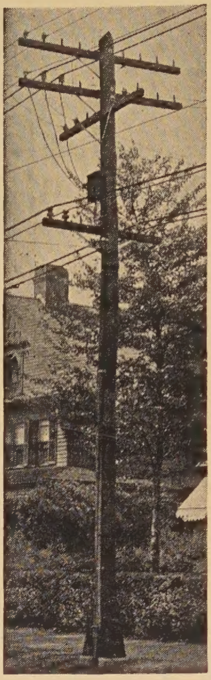
*BELL TELEPHONE SYSTEM*

*You are cordially invited to visit the Bell System exhibit at the Golden Gate International Exposition, San Francisco*

AMERICAN TELEPHONE & TELEGRAPH CO. AND ASSOCIATED COMPANIES
BELL SYSTEM

## Still Serviceable After Fifteen Years

In 1924 this chestnut pole required replacement or salvage because of ground-line decay. The Williams Pole Mount salvage method was employed. Today the pole appears sound enough for another 15-year period. Equivalent Williams Pole Mount construction now would cost from $38.00 to $40.00 for grouped jobs to about $45.00 for single poles—with some extras for freight beyond 200 miles and for transportation to relatively inaccessible pole locations.



Spreading this salvage cost over the demonstrated life gives annual maintenance cost of about $3.00 to date, reducible to about $1.50 by extending the useful life to 1950. Then the Pole Mount unit on permanent concrete base is ready to receive replacement pole at same location at cost of perhaps $5.00 plus pole and overhead changes—or the entire unit may be salvaged for use elsewhere.

Figure against the above the cost of replacement of pole otherwise required in 1924 to carry trolley feeders, telephone and light and power services with riser pipe, and question whether that replacement would last until 1950. You then have the answer as to which method is cheaper. About 7,000 successful installations in United States and Canada prove we have an economic salvage construction device and method. Used also to support new poles to meet special anchorage conditions requiring development of full strength of pole.

*Investigate the economy of Pole Mount construction.*

*Send for M.I.F. Pole Hardware Specialties Catalog featuring also:—Pole Stubbing Clamps—Cable Messenger Clamps—Malleable Secondary Racks and Clevises—Screw Anchors—Transformer Gain Plates—Insulated Hangers—Tubular Pole Fittings—Crossarm Gains—Through-bolt Guy Hooks and Accessory Eye Nuts, etc.*

**MALLEABLE IRON FITTINGS COMPANY**
**Pole Hardware Dept.** [ Factory and New England Sales Office ] **Branford, Connecticut**
New York Sales Office: Thirty Church Street
Canadian Mfg. Distributor:
LINE & CABLE ACCESSORIES, Ltd., Toronto

## NOISE MEASUREMENT

In determining the true causes of observed sound levels and in measuring the levels produced by apparatus, the new "Test Code for Apparatus Noise Measurement" will be found of great value in establishing uniform methods of conducting and reporting such tests.

The following subjects are covered: radiation of sound, room effects, ambient sound levels, instruments standards, factory tests, measurement positions and field investigations.

This Test Code was developed by the Subcommittee on Sound of the A.I.E.E. Standards Committee and was published in March, 1939. Copies are obtainable at a cost of 30 cents each (50% discount to A.I.E.E. members on single copies). Address H. E. Farrer, Secretary, Standards Committee—

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS
33 West 39th St. New York, N. Y.

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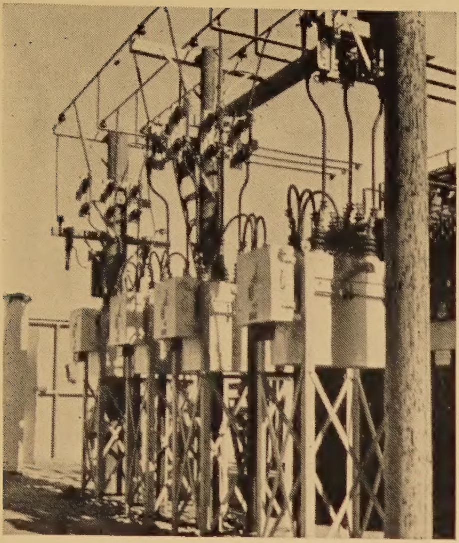
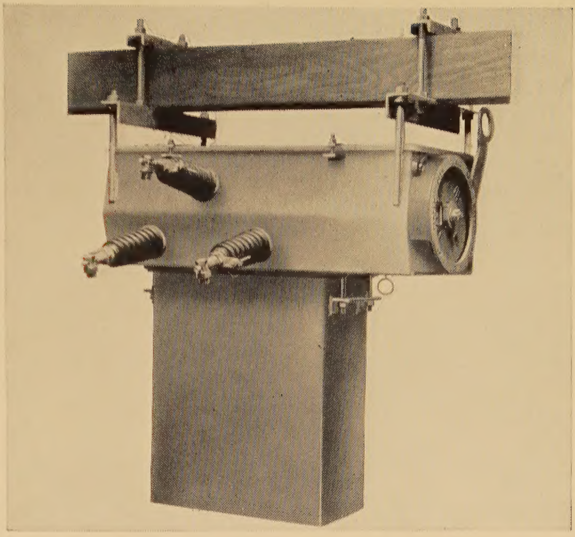


Type AKE breakers in 4000 kva substation serving the Gayway at San Francisco Exposition.

## ATTENTION Delegates to San Francisco AIEE Convention!

See all this reliable high-voltage equipment at our exhibit on Treasure Island while you attend the AIEE Convention in San Francisco June 26–30.



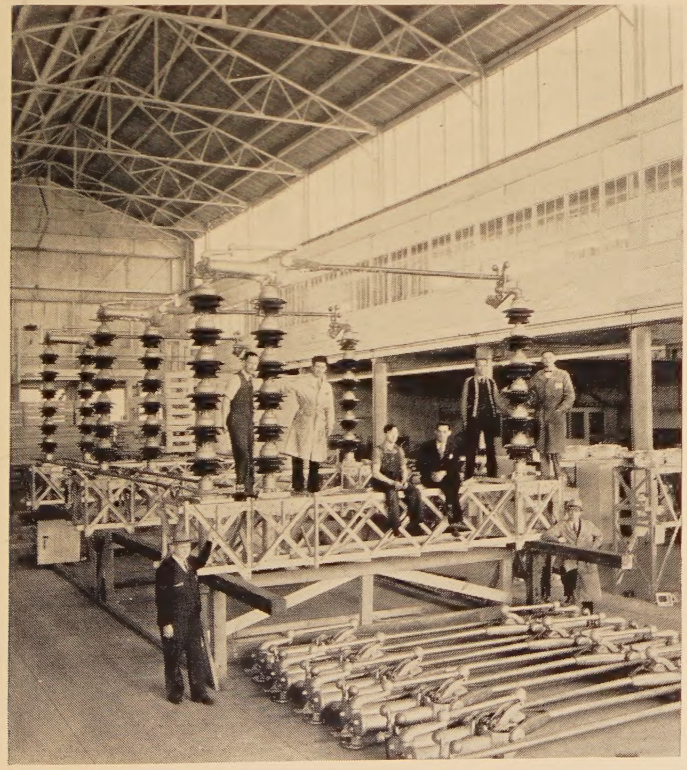
Automatic Service Restorer for rurel or low-revenue distribution lines

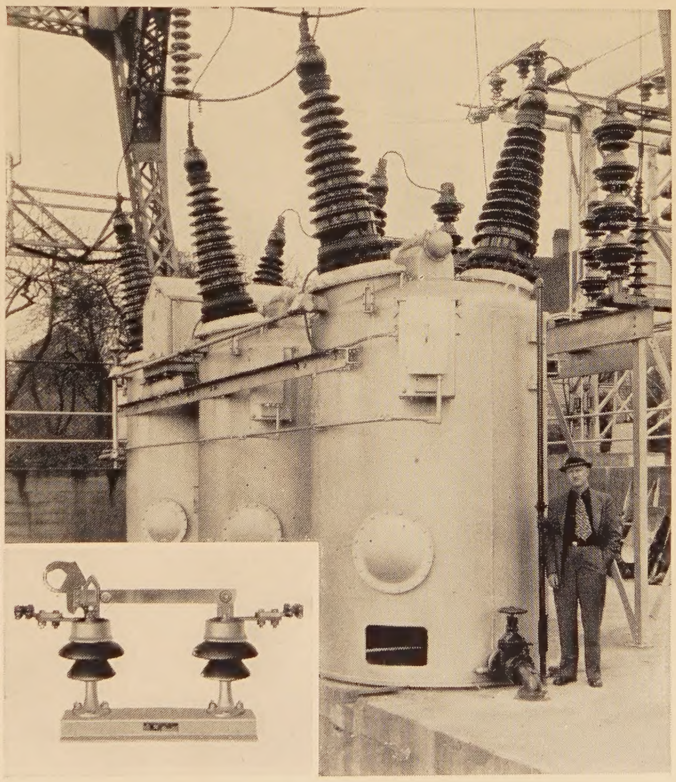
# YES, MORE for YOUR MONEY!

## with these Switches and Oil Circuit Breakers

You can have full circuit protection, low first cost and less maintenance with Pacific Electric Oil Circuit Breakers. You can have easy, positive operation with Pacific Electric Air-Break Switches.

Stop in at our exhibit at the San Francisco Fair. See for yourself why scores of utilities rely upon Pacific Electric equipment for safe, sure operation of their systems. Write now for full details.





Lower left: Air-Break Switches ready for Boulder Dam equipped with our MG-6 Motor Control and high-pressure contacts. Above: Type RWE Oil Circuit Breaker, 161 kv. equipped with our MW-40 Motor Control. Installed in Washington. Insert: Indoor Disconnect, 4000 a., equipped with clamp contacts for full load carrying.

You owe it to your company to obtain the full details on the money-saving, reliable Pacific Electric equipment while you are in San Francisco. See our exhibit. Visit our plant. Ask for bulletins describing these big-value Oil Circuit Breakers and Switches.

**Pacific Electric Mfg. Corporation.**

5815 THIRD ST., SAN FRANCISCO, CALIF. DUNES HIGHWAY, GARY, INDIANA

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# OKONITE RUBBER INSULATION IS *Custom Built*

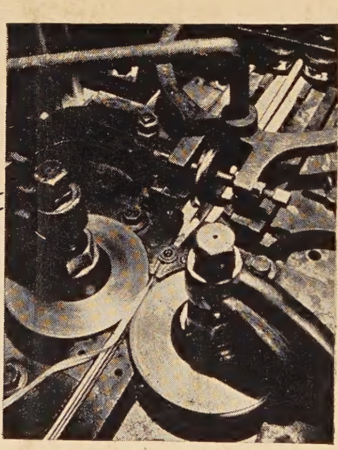
**There are so many precise refinements employed in selecting the materials and in the details of the manufacture of Okonite rubber insulation that it often is referred to as "custom-built". » » Among these precise refinements are:**

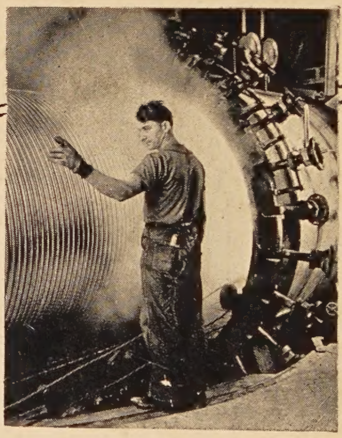
The thorough washing that the Wild Up-river Fine Para rubber undergoes

The long periods that the washed rubber is hung for natural and unhurried drying

The constant gauging of the Okonite compound as it is calendered between heavy rolls

The foot-by-foot inspection of the calendered strips after the tin backing has been applied


The conductor being insulated with these strips and open to inspection all the time


Vulcanization in continuous metal mold

**Electrical and chemical inspections and tests during and after completion of every cable exceed, by far, the specification requirements of any purchasing or standardizing bodies. It is significant that one out of every six Okonite factory men is employed in inspection or research. » » Is it any wonder that Okonite is called the "custom-built" insulation?**

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*Founded 1878*

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